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MASS TRANSFER TO A FALLING LIQUID ON A FLAT PLATE
WITH TRANSVERSE CONCENTRATION GRADIENTS AND
WITH CONSTANT HOLD-UP AND VARIABLE LIQUID FEED

by

JACKIE JOE LONSINGER

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INTRODUCTION

Mass transfer is basic to many of the major operations in Chemical Engineering. In mass transfer, one or more materials is transferred between phases, where the phases frequently are vapor-liquid, vapor-solid, liquid-liquid, liquid-solid, or solid-solid. Examples of mass transfer include the scrubbing of natural gas in which the heavier hydrocarbons are removed from the gas stream by a liquid absorbent, removing obnoxious or valuable gases from air with carbon, and cooling a space vehicle by the evaporation of a solid into the atmosphere.

The rate of removal of small concentrations of a given absorbable component from a large volume of carrier gas by absorbing the given component into a liquid may be controlled or limited by either or both of at least two factors; a) the gas phase movement of the dilute component through the carrier to the liquid-gas interface may be slow, or b) the transfer of the absorbable component through the gas phase stagnant layer may be slow. A system which may make this operation more economically attractive is one in which the liquid hold-up in the transfer equipment is not totally dependent upon the liquid flow rate. Such a system would offer the advantage of allowing sufficient time for mass transfer to take place when rates of transfer are low. Mass transfer equipment of this type was used in this experiment.

The basic theoretical studies of mass transfer have been, and are presently, confined to systems of simple geometry such

as flat plates, spheres, and cylinders. Spheres and cylinders are studied because of their important industrial uses in fluid beds and wetted wall columns. Flat plates have found little large scale use and are studied mainly because they possess the simplest geometry.

The approach for studying mass transfer in the above-mentioned geometries has been either two-dimensional or axis symmetrical (See PLATE I, Figure 1). The flat plate mass transfer system discussed in this paper was three dimensional in that the liquid concentration gradient and direction of flow was perpendicular to the vapor concentration gradient and direction of flow (See PLATE I, Figure 2).

Review of Literature

Johnstone and Pigford (8) have derived equations which describe the transfer of a material into a falling liquid film. Bromley, Read, and Bupara (9) used vertical nylon strings to obtain dispersion of an absorbent in the form of a sheet. Powell and Griffiths (10) used a linen covered surface to evaporate water into a passing air stream. The linen was used to keep the entire surface wet. Chambre and Young (12) have shown good agreement between experimental data and the boundary layer prediction of mass transfer to a flat plate on which a chemical reaction accompanied the mass transfer.

Brian et al. (13) and Friedlander and Litt (14) have recently shown that the penetration theory for mass transfer compares equitably with the film theory for mass transfer to

flat plates. Rohsenow and Choi (2), using the boundary layer approach, described a system in which a solid flat plate of constant concentration was sublimed into a passing air stream. Bird, Stewart, and Lightfoot (1) have summarized a great portion of the boundary layer theory in relationship to flat plate mass transfer.

No work on three-dimensional systems other than those with an axis of symmetry was found in this search.

Objectives

The objectives of this research project were:

- 1) To study the absorption of water from air by glycols in vertical flat plate geometry under conditions of constant liquid surface hold-up through a range of liquid flow rates.
- 2) To correlate the results of this study in order to obtain a procedure for estimating the mass transfer in equipment of this type.

DESCRIPTION OF EQUIPMENT

The physical layout of the components of the system are shown in PLATE II. The components were enclosed in a chamber nine feet long, six feet wide, and nine feet high. The walls of the chamber were impervious to water vapor.

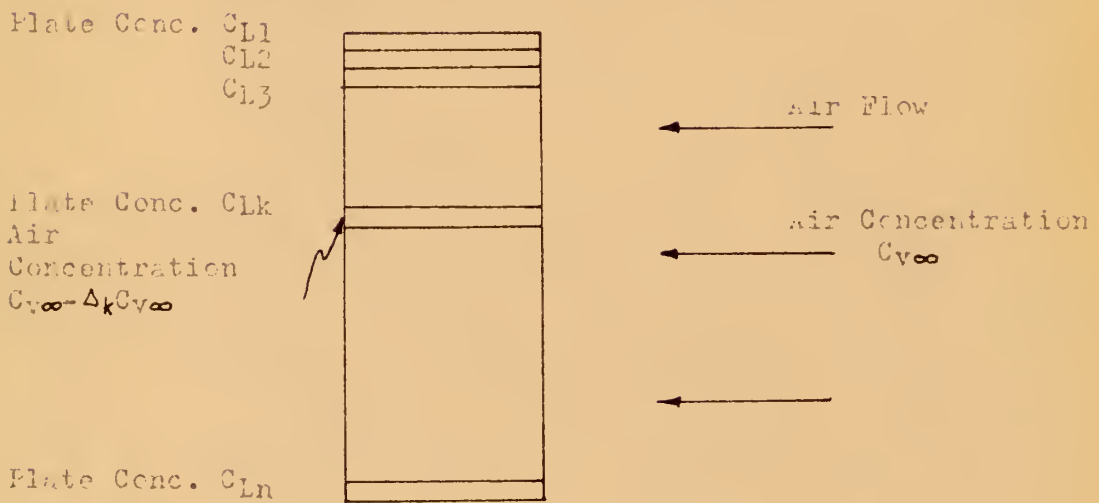
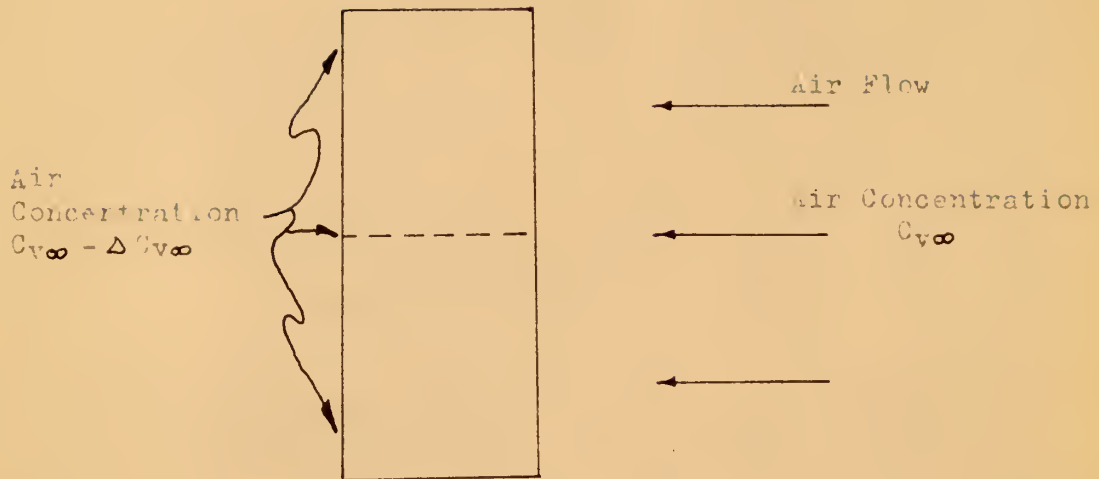
The plate towers were fed the lean solutions, propylene glycol in tank 1 and ethylene glycol in tank 2, through three-sixteenths inch copper tube syphons. The syphons were equipped

EXPLANATION OF PLATE I

Flat plate mass transfer systems.

- Figure 1. Illustration of usual system for study of mass transfer to a flat plate. The plate is of concentration C_L throughout. The air is of concentration C_{∞} at the right of the plate and $C_{\infty} - \Delta C_{\infty}$ at the left of the plate.
- Figure 2. Illustration of the system proposed for studying the mass transfer in this experiment. Concentration of any one horizontal element is constant. The elements become more concentrated toward the bottom of the plate. The air concentration is C_{∞} at the right of the plate, but at the left is dependent upon the vertical position on the plate.

FIGURE 1

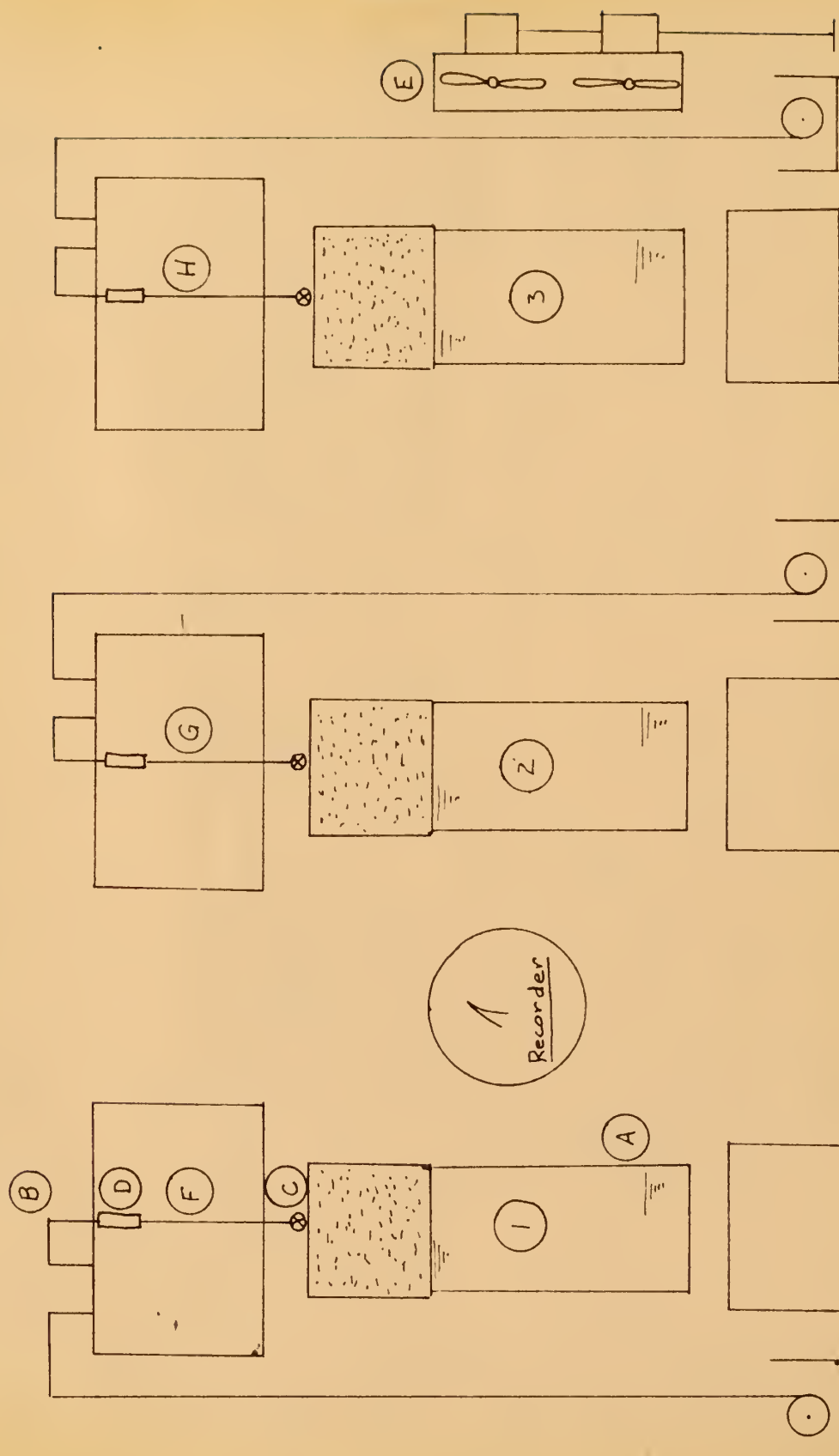


EXPLANATION OF PLATE II

Illustration of experimental equipment layout.

1. The propylene glycol tower
2. The ethylene glycol tower
3. The water supply tower
- A. The tower proper
- B. Three-sixteenths inch copper syphon
- C. Distributor
- D. Teflon collars mounted in steel pipe
- E. Two seventeen inch fans
- F. Propylene glycol tank
- G. Ethylene glycol tank
- H. Make-up water tank

PLATE II



with a small copper valve, to control the lean solution flow rate. To obtain freedom of movement, the syphons were mounted on polyurethane foam floats and were guided by Teflon collars mounted in a three-eighths inch steel pipe. Air was blown past tower 3, tower 2, and tower 1, in that order.

The relative humidity was controlled by feeding pure water from tank 3 down tower 3, and evaporating the water with the moving air stream.

The air flow rate was controlled by using two seventeen inch fans, one mounted directly above the other. The fans were connected in parallel and the speed of the fans was controlled by connecting both to the same rheostat.

Shown in PLATE III is the detail of a plate tower. The liquid flowed through the chipped stoneware packing, to become evenly distributed. From the packing the liquid flowed into the corduroy cloth cover and down the tower. As the liquid proceeded down the tower, it became richer in water due to mass transfer from the air. The water rich solution was then collected at the bottom of the tower.

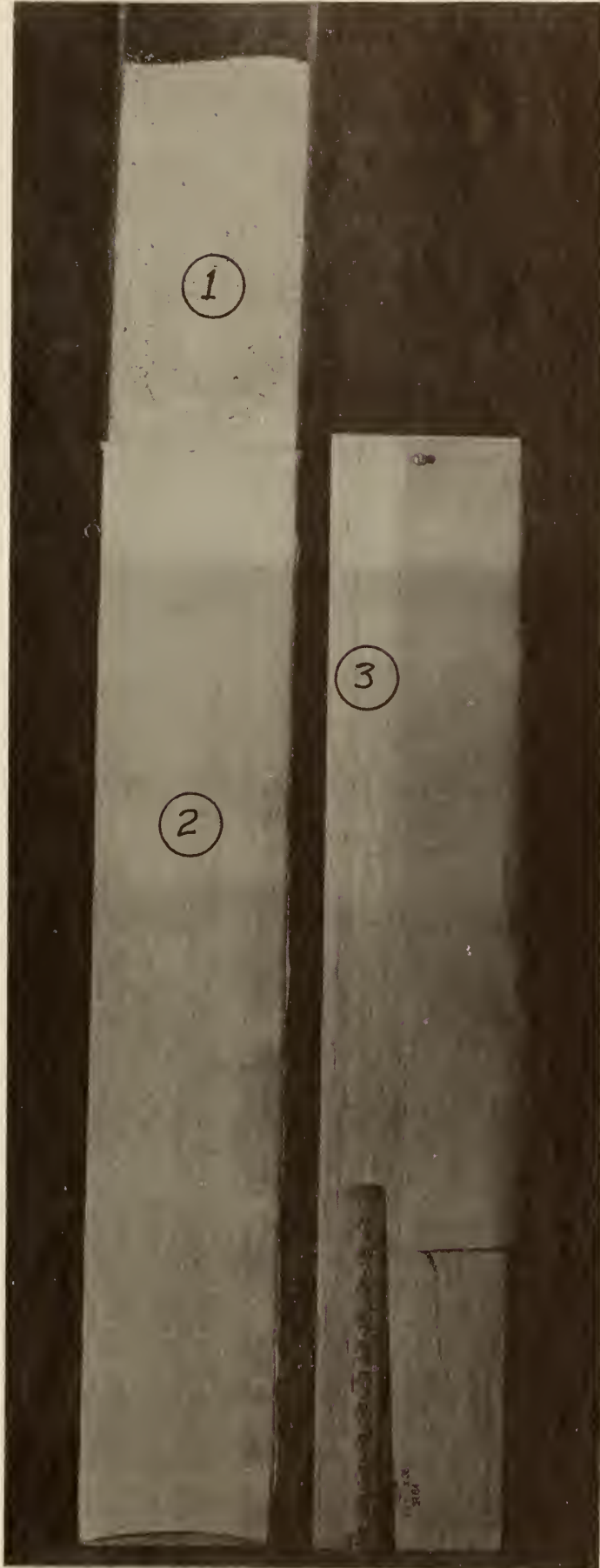
The corduroy cloth covering served two purposes. It acted as a surface agent to minimize channelling, i.e., it served to spread the liquid more evenly over the plate. It also acted as a hold-up agent and because of this property, the total amount of liquid on the plate was essentially independent of the solution flow rate over the range studied.

EXPLANATION OF PLATE III

Detail of the plate tower.

1. Chipped stoneware distributor.
2. Corduroy cloth covering.
3. Balsa wood support for cloth covering.

PLATE III



OPERATIONAL PROCEDURE

The method of operation used was as follows:

- 1) The flow of lean solution was started in the syphon tubes. The flow rate was then adjusted to the desired value.
- 2) The flow of water was started on the water tower. The water flow rate was set by hand and an equilibrium relative humidity established. That is, for high relative humidity an amount in excess of that which the tower would evaporate was fed. For low relative humidity the feed was shut off completely. For intermediate relative humidity a flow rate between the extremes was used.
- 3) The air flow was then started by adjusting the rheostats connected to the fans.

Experimental Design

The procedure for taking data samples was designed with the solution concentration as the unknown variable. The air flow rate was set at a chosen value. At this air flow rate, the incoming solution rate was varied. At each of the incoming solution rates, the relative humidity was varied. Then, at each relative humidity, solution samples were taken on the tower surface.

A nested table resulted which appeared as follows.

Table 1. Experimental design table.

Data Set I									
Air Flow Rate 1									
Solution : Sample*	Solution Rate 1 : RH 1:RH 2:RH 3			Solution Rate 2 : RH 1:RH 2:RH 3			Solution Rate 3 : RH 1:RH 2:RH 3		
Inlet	x	x	x	x	x	x	x	x	x
6 in.	x	x	x	x	x	x	x	x	x
12 in.	x	x	x	x	x	x	x	x	x
18 in.	x	x	x	x	x	x	x	x	x
24 in.	x	x	x	x	x	x	x	x	x
30 in.	x	x	x	x	x	x	x	x	x
Outlet	x	x	x	x	x	x	x	x	x

* The solution samples were taken at the specified distance down the tower. Replicate samples were taken approximately an hour after the initial samples were taken.

Sampling Procedure and Measurement of Variables

The variables recorded were (1) temperature, (2) relative humidity, (3) outlet solution flow rate, (4) solution concentration at six inch intervals including inlet and outlet, (5) main air stream velocity, and (6) the barometric pressure. The thickness of the liquid film on the tower was measured after all the concentration data had been gathered.

The methods of measuring the variables and analyzing the samples were as follows:

1) Temperature.

The temperature was recorded for each run at the time of solution sampling. A permanent record was kept on a Bristol recorder. A typical recorder chart is shown in the Appendix, PLATE XXXIII.

Temperature calibration was performed with a mercury thermometer. Table A-1 in the Appendix shows the results of the calibration.

2) Relative Humidity.

The relative humidity was measured with a Bristol temperature-humidograph, which incorporated a wood hygrometer. A typical recorder chart is shown in the Appendix, PLATE XXXIII.

The recorder was calibrated for relative humidity using a sling psychrometer. The results of the calibration are shown in Table A-1 in the Appendix.

3) Outlet Solution Flow Rate.

The outlet solution flow rate was measured by collecting the discharge from the tower for a period of two minutes. The solution was collected in a cylinder graduated in tenths of a milliliter, which made accurate estimation to the nearest five-hundredths of a milliliter possible.

4) Solution Samples.

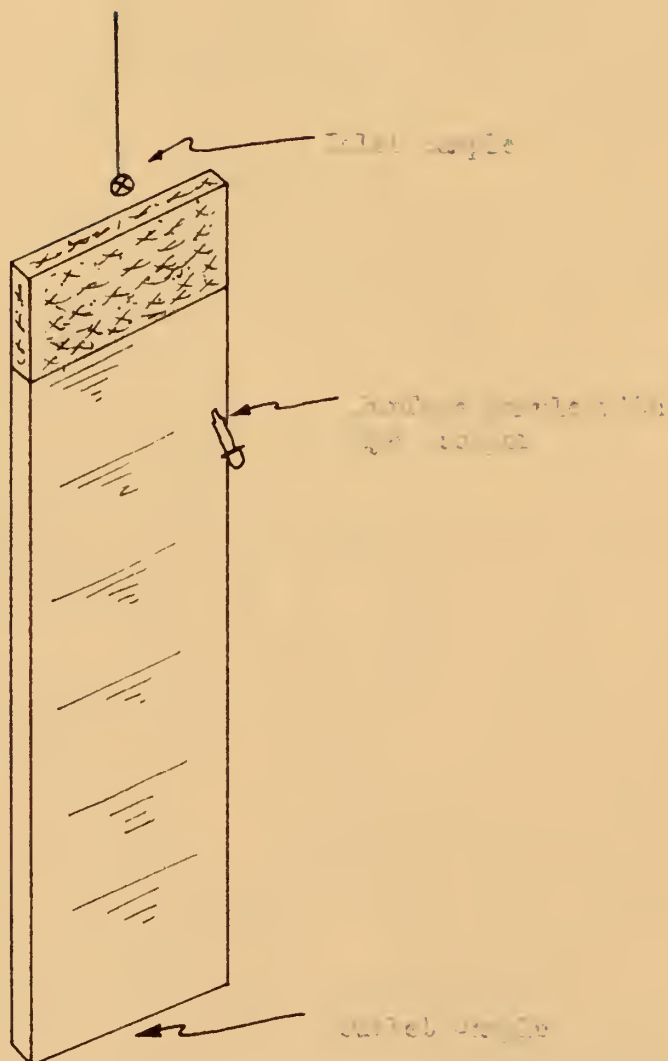
The solution samples were taken in small glass bottles. The inlet and outlet samples were collected directly from the feed syphon and tower discharge, respectively. The samples taken from the surface of the tower were taken with an eye dropper (See PLATE IV). The sample taken was an average of the solution in the immediate vicinity of the sampling point.

To show that the sample was an average, samples

EXPLANATION OF PLATE IV

Illustration of sampling method and sampling equipment.

PLATE IV



Internal Structure of

Sample of Sample 1000

Internal Structure of

were taken with an eye dropper which had been drawn to a fine point so that a sample from "inside" the cloth was obtained (See PLATE IV). The results, as summarized in Table A-2 in the Appendix, showed the sample analysis to be essentially the same.

The surface samples were taken at six inch intervals down the tower. The samples were taken on alternate sides for the initial run (See PLATE V). The alternation was reversed for the replicate run (See PLATE V).

A series of transverse samples showed a pointed or possibly parabolic distribution (See Table A-5 and PLATE XXIV in the Appendix). An average concentration was calculated (Appendix, Table A-6) and the samples were then taken at a distance from the leading edge corresponding to the average composition.

The samples were analyzed on a refractometer. The calibration of the refractometer was performed with known samples. PLATES XXV and XXVI in the Appendix are results of the calibration.

To insure against the possibility of the sample absorbing water while being placed on the refractometer crystal, a series of runs were made in which samples of various composition were placed on the crystal and the refractive index read. The refractometer was then opened to allow solution contact with the atmosphere for various lengths of time and then the refractive index

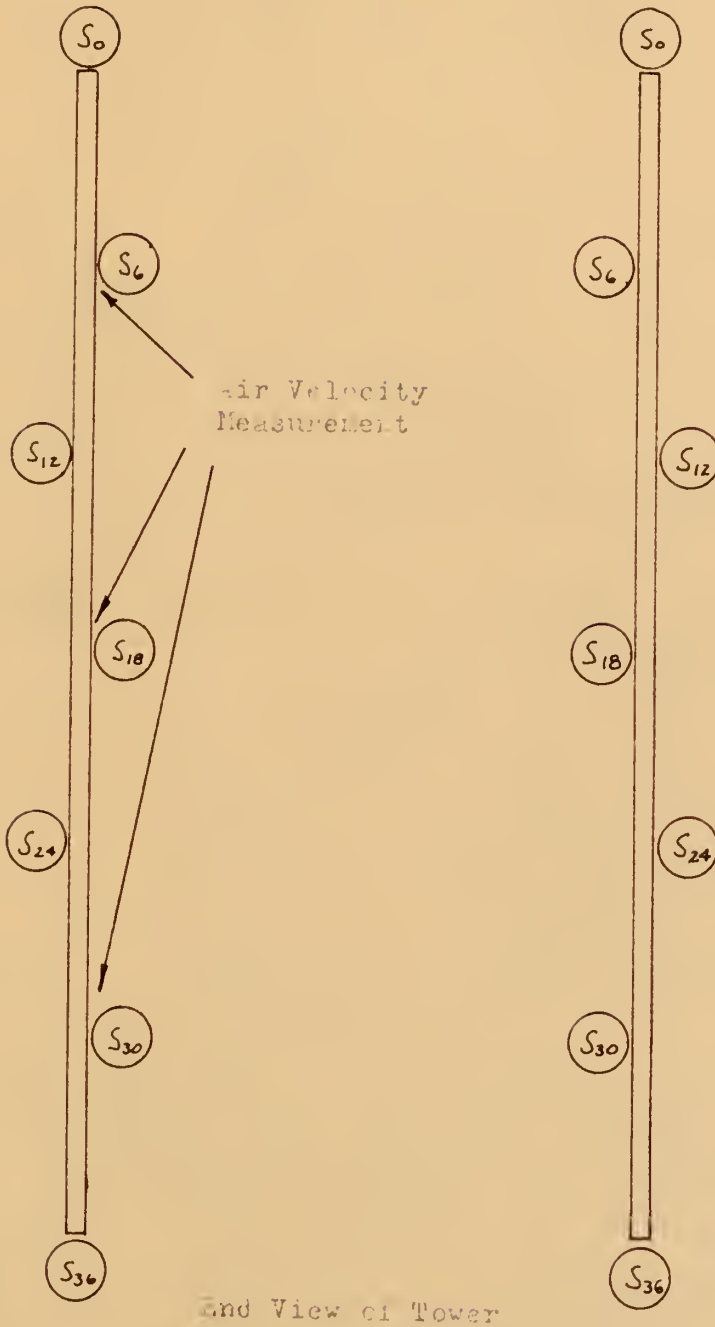
EXPLANATION OF PLATE V

Illustration of sampling positions for liquid samples and of position of air flow measurement.

PLATE V

Initi 1 Run

Replicate Run



was re-read. Table A-3 in the Appendix shows that the sample did not absorb water while being analyzed.

5) Main Air Stream Velocity.

The main air stream velocity was measured with a vane anemometer. The velocity was measured every twelve inches, starting at six inches from the top, by placing the anemometer into the air stream immediately before the leading edge of the tower (See PLATE V).

6) Barometric Pressure.

The barometric pressure was read on a mercury barometer at the time of solution sampling.

7) Liquid Film Thickness Measurement.

The measurement of the thickness of the liquid film was made on the assumption of an even distribution of solution on the tower surface. The measurement was made by weighing the tower without solution feed and then weighing the tower while being fed glycol solutions at various feed rates and viscosities. The apparatus used for weighing the tower is shown in PLATE VI.

THE MASS TRANSFER MODEL

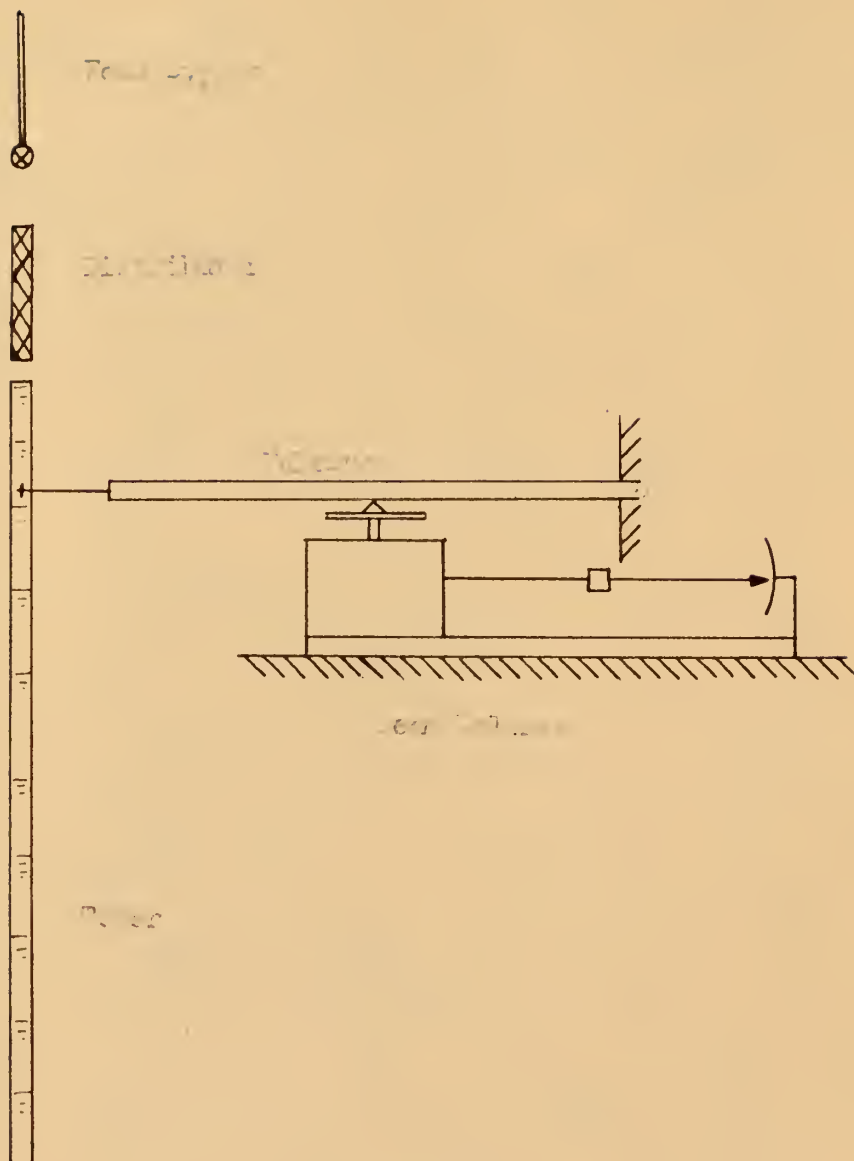
The model proposed for the description of the mass transfer was divided into three steps. The steps were:

- 1) Mass transfer through the air by bulk diffusion and molecular diffusion.
- 2) Mass transfer from the surface of the liquid into the liquid by molecular diffusion.

EXPLANATION OF PLATE VI

Weighing apparatus for liquid film thickness.

PLATE VI



- 3) Equating the rates of (1) and (2) by an iterative procedure on a digital computer.

PLATE VII shows the co-ordinate system and nomenclature used.

Air Side Mass Transfer

It was assumed that the vertical velocity of the liquid was constant in any given horizontal plane (x direction in PLATE VII). Also, it was assumed that the liquid concentration did not vary in any given horizontal plane (also x direction in PLATE VII). These assumptions allowed the system to be analyzed as a series of small finite flat plates (See PLATE VIII), each plate being a thin section of many plates of different composition.

For mass transfer with only water transferring and assuming that the physical properties of air are constant, i.e., ρ , μ , and D , and that the air flow is laminar, then for each finite section (PLATE VIII, note A), the boundary layer equations become,

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0 \quad (1)$$

$$v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} = \nu \frac{\partial^2 v_x}{\partial y^2} \quad (2)$$

$$v_x \frac{\partial c_v}{\partial x} + v_y \frac{\partial c_v}{\partial y} = D \frac{\partial^2 c_v}{\partial y^2} \quad (3)$$

Solving (1) for v_y and substituting into (3) yields,

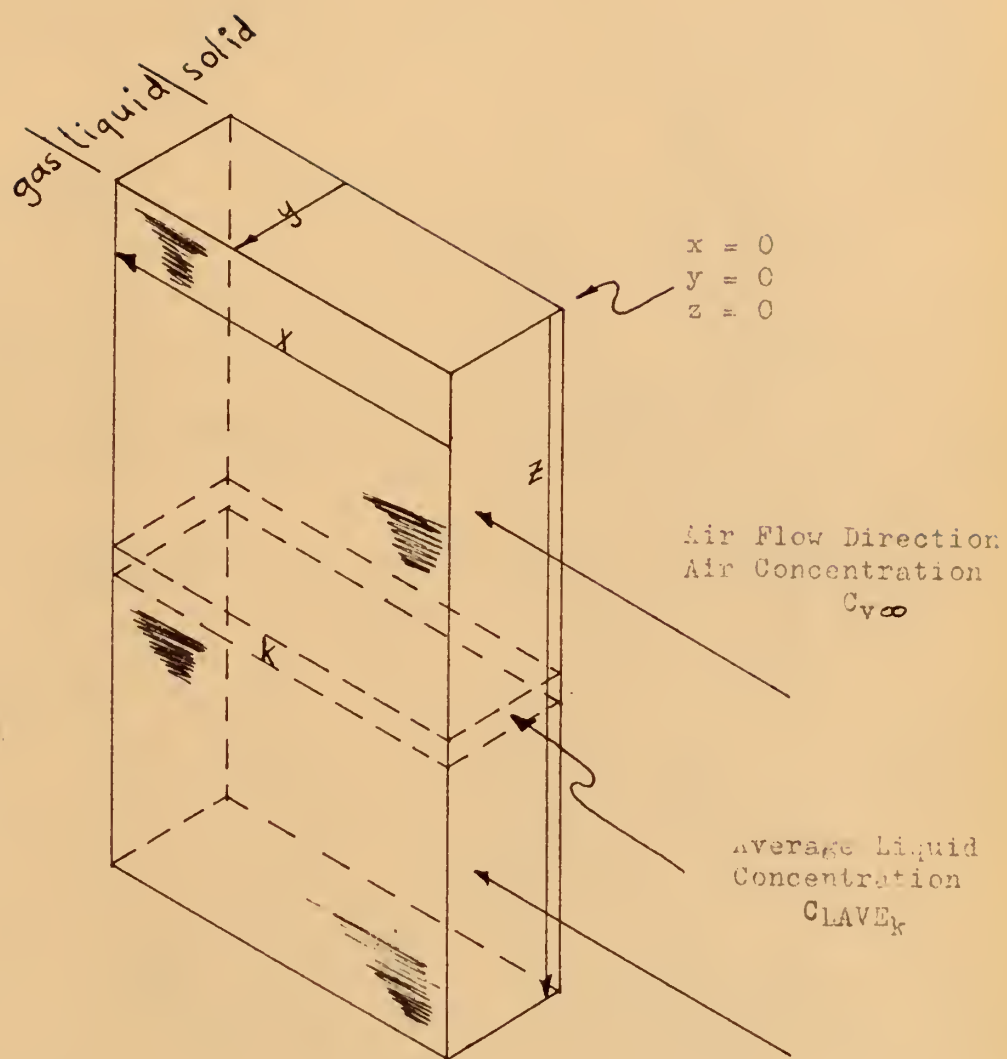
$$v_x \frac{\partial c_v}{\partial x} - \left(\int_0^y \frac{\partial v_x}{\partial x} dy \right) \frac{\partial c_v}{\partial y} = D \frac{\partial^2 c_v}{\partial y^2} \quad (4)$$

EXPLANATION OF PLATE VII

Illustration of a large section of liquid falling film. Across front of element k:

1. Liquid surface concentration: C_{Lk}
2. Vapor surface concentration: C_{vk}

PLATE VII

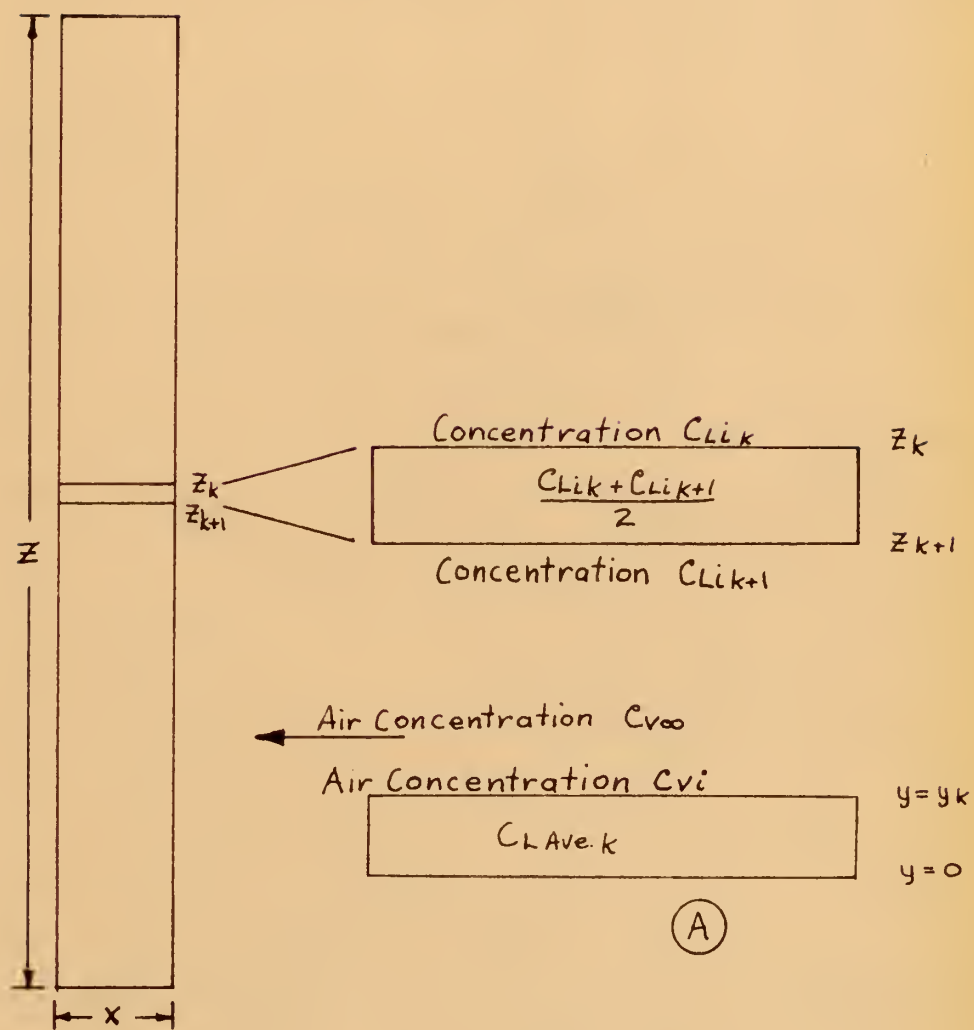


EXPLANATION OF PLATE VIII

Illustration of liquid concentration for a finite division.

- A. The cross section of a division showing air surface concentration and average liquid concentration.

PLATE VIII



V_y has been assumed equal to zero at $y = 0$ in (4) since mass transfer rates are low.

Bird, Stewart, and Lightfoot (1) have integrated (4) assuming similar linear profiles for velocity and concentration. The result of the integration was:

$$N = \frac{D(C_{v\infty} - C_{vi})(S_c)^{\frac{1}{3}}}{\sqrt{12} \sqrt{\nu} x / \sqrt{v_{\infty}}} \quad (5)$$

where N = moles of water transferred per unit time per unit area.

D = diffusivity of water vapor in air, $\frac{\text{ft}^2}{\text{hr}}$.

$C_{v\infty}$ = concentration of water vapor in air in the main stream, $\frac{\text{lb-moles}}{\text{cubic foot}}$.

S_c = Schmidt number, $\frac{\mu}{D\rho}$, dimensionless.

ν = kinematic viscosity, $\frac{\text{ft}^2}{\text{hr}} =$.

v_{∞} = main air stream velocity, $\frac{\text{ft}}{\text{hr}}$.

C_{vi} = concentration of water vapor in air at the liquid surface, $\frac{\text{lb-moles}}{\text{cubic foot}}$.

x = plate width, feet.

Liquid Side Mass Transfer

For the liquid side mass transfer it was assumed that the liquid diffusion coefficient was constant and that liquid mixing was not appreciable in the direction perpendicular to the face of the plate (y direction). Also, it was assumed that the liquid concentration at the interface of the film and the column

support was the initial concentration, C_{Lo} , throughout the length of the column.

Johnstone and Pigford (8) have shown for diffusion of a solute through a falling liquid film, that Fick's law,

$$\frac{\partial C_L}{\partial \theta} = D_L \frac{\partial^2 C_L}{\partial y^2} \quad (6)$$

can be integrated assuming a parabolic distribution of velocity to give an equation of the form,

$$\frac{C_{Li} - C_{LAve}}{C_{Li} - C_{Lo}} = \frac{K_2}{e^{K_3 P}} \quad (7)$$

where C_{Li} = liquid surface concentration

C_{LAve} = average liquid concentration

C_{Lo} = initial liquid concentration

K_2 & K_3 = constants dependent upon system geometry.

and
$$P = \frac{D_L \theta}{Y^2} \quad (8)$$

where D_L = diffusivity of water through glycol

θ = time of contact of vapor phase with liquid phase

Y = thickness of the liquid film.

The liquid diffusivity, D_L , was assumed to follow the expression given by Wilke and Chang (11):

$$D_L = \frac{(7.4 \times 10^{-8}) T (\alpha M)^{\frac{1}{2}}}{\mu V^{0.6}} \quad (9)$$

where T = absolute temperature, $^{\circ}K$

M = molecular weight of solvent

V = specific volume of solute, $\frac{ml}{g-mole}$

α = experimental parameter

μ = solution viscosity, centipoise

Equating Air and Liquid Side Mass Transfer

The equilibrium and viscosity relationships were approximated with second degree polynomials (See PLATES XXVII, XXVIII, XXIX, and XXX, Appendix). The relationship between relative humidity fraction and mass fraction of water in the glycol solutions was for ethylene and propylene glycol respectively,

$$RH(\text{frac}) = 3.0(c_{Li}) - 2.5(c_{Li})^2 \quad (10)$$

$$RH(\text{frac}) = 3.4(c_{Li}) - 4.0(c_{Li})^2 \quad (11)$$

where R.H. (frac.) = relative humidity expressed as a fraction.

C_{Li} = water concentration at the liquid surface.

The relationship between viscosity and mass fraction water in the glycol solutions for ethylene and propylene, respectively, was:

$$\mu_E = 11.5 - 45(c_{LAve}) + 100(c_{LAve})^2 \quad (12)$$

$$\mu_P = 26.5 - 106(c_{LAve}) + 150(c_{LAve})^2 \quad (13)$$

where μ = liquid viscosity, centipoise

c_{LAve} = average concentration

With the above equations it was then possible to calculate the viscosity for any solution concentration and also to calculate

the relative humidity of air in equilibrium with any liquid solution concentration.

The relative humidity permitted the calculation of the water vapor in air, C_v , in pound-moles per cubic foot by the following method.

$$\left(\frac{\text{R.H.}}{100} \right) (\text{vapor pressure of water}) = \text{partial pressure of water} \quad (14)$$

$$\left(\frac{\text{Partial pressure}}{\text{total pressure}} \right) = \text{mole fraction water} \quad (15)$$

$$\left(\frac{\text{pound moles water vapor}}{\text{volume per pound mole of air-water}} \right) = C_v \left(\frac{\text{pound moles water}}{\text{cubic foot}} \right) \quad (16)$$

Under the operating conditions of the experiment the vapor pressure of water was 26.5 millimeters of mercury and the total pressure was the average pressure during all runs, Sample Calculations A-1, Appendix. The volume per pound mole of air and water vapor was calculated assuming ideal gas behavior.

The procedure for solving the mass transfer equations (5) and (7) on the computer was as follows:

- 1) The tower was divided into seventy-two one-half inch finite divisions. The liquid concentration was assumed constant over each of the divisions.
- 2) The pounds of water absorbed using the liquid concentration at the inlet of the division was calculated using equations (5), (10), (14), (15), and (16).
- 3) The new solution concentration for the same division was

then calculated using the solution flow rate and the pounds of water absorbed.

- 4) The average of the solution concentrations in (2) and (3) was computed. This average concentration was then used in equation (7) to compute the concentration at the solution surface. Then equations (5), (10), (14), (15), and (16) were used to calculate a new value of pounds of water absorbed for the same division.
- 5) The procedures in (3) and (4) were continued until the difference between the old and the new value of pounds of water absorbed was less than 10^{-5} pounds.
- 6) As soon as the conditions in (5) were met, the computer was then sent to the next division. This process was continued until the concentration and the pounds of water absorbed were calculated for each of the seventy-two divisions.

The constants for each equation and each glycol solution were grouped previous to programming. Equation (5) became

$$N = K_1 (C_{V\infty} - C_{Vi}) (V_{\infty})^{\frac{1}{2}} \quad (17)$$

where
$$K_1 = \frac{D (S_c)^{\frac{1}{2}}}{\sqrt{12} \sqrt{VX}}$$

Equation (9) became

$$D_L = \frac{K_4}{\mu} \quad (18)$$

where
$$K_4 = \frac{(7.4 \times 10^{-8}) T (\alpha M)^{\frac{1}{2}}}{V^{0.6}}$$

For a given division the contact time between the solution and the air was calculated by the volumetric flow rate.

$$\Theta = \frac{V_A}{\dot{V}} \quad (19)$$

where V_A = volume available for flow of liquid

= (length) (perimeter) (liquid film thickness)

\dot{V} = volumetric flow rate

= (mass flow rate) $\frac{1}{\text{liquid density}}$

The flow sheet for programming and the IBM SOAP II output program are shown in the Appendix, PLATES XXXI and XXXII, respectively. The input-output format is shown in Table A-7, Appendix.

RESULTS

Liquid Film Thickness Measurement Results

Table 2 shows that the quantity of liquid on the tower was not the same as would be expected from the calculations for a falling liquid film. The calculated liquid hold-up was calculated using the expression (1), $\gamma = \left(\frac{3\mu\Gamma}{\rho^2 g_c} \right)^{\frac{1}{3}}$, for the film thickness on the basis of a cloth free surface.

The determination of the experimental liquid hold-up is shown in Sample Calculations A-2, Appendix. The calculated liquid hold-up calculations are shown in Sample Calculations A-3, Appendix.

The thickness of the liquid film was calculated from the results of Table 2. The volume occupied by the cloth was added

to the volume of liquid on the tower surface to calculate the actual liquid film thickness. Sample Calculations A-2 in the Appendix summarizes the calculations. The results of the indirect measurement of liquid film thickness are summarized in Table 3.

The average value of the total liquid film thickness, 0.089 cm., was used in equations (8) and (20) for the thickness of the liquid film.

Table 2. Liquid hold-up on the tower.

Feed Rate	Run Number	Experimental Liquid Hold-up	Calculated Liquid Hold-up
.075	3	218	74
.130	6	227	100
.151	2	228	93
.167	9	236	75
.192	5	231	114
.356	4	252	141
.413	8	248	101
.537	7	250	110

Table 3. Liquid film thickness.

Run Number	: Liquid Flow Rate	:	Film Thickness, cm.			:	Cloth**
			1*	:	2*	:	3*
1	0.254		0.073	-	-		0.088
2	.151		.073	-	-		.088
3	.075		.071	-	-		.084
4	.356		-	0.081	-		.095
5	.192		-	.074	-		.087
6	.130		-	.073	-		.089
7	.537		-	-	0.076		.090
8	.413		-	-	.075		.090
9	.167		-	-	.071		.086
Ave.	-		-	-	-		.089

* Film Thickness Measurement 1 was made with a 10.8 per cent water-propylene glycol solution with a viscosity of 16 centipoise. Film Thickness Measurement 2 was made with a 4.3 per cent water-propylene glycol solution with a viscosity of 23 centipoise. Film Thickness Measurement 3 was made with a 17 per cent water-ethylene glycol solution with a viscosity of 7 centipoise.

** The cloth cover had a thickness of 0.066 cm. porosity was 0.779 as calculated in the Appendix, Sample Calculations A-4.

Experimental Results

Table 4 gives the values of the variables at which data were taken for ethylene glycol. Table 5 is the similar table for propylene glycol. Replicate runs were averaged together; runs that were not replicated were reported alone.

The results of the concentration measurements were plotted against length down the tower. Three representative curves of each ethylene and propylene glycol solutions are shown in PLATES IX through XIV. The curves show the concentration increases with length down the tower and that the greatest amount of water was transferred in the upper part of the tower where the concentration gradient was the greatest.

Table 4. Operating conditions for ethylene glycol runs.

Air Flow Rate = 20,400 feet/hour				
Run Number	Inlet Solution Flow Rate (lbs./hour)	Inlet Concentration (mass fraction water)	Relative Humidity (%)	
9	0.0929	0.065	48	
10 , 11	.127	.065	50	
12 , 13	.114	.067	60	
14 , 15	.941	.067	66	
16 , 17	.256	.066	66	
18 , 19	.195	.061	61	
20 , 21	.145	.055	55	
22 , 23	.302	.054	49	
24 , 25	.287	.055	64	
, 26	.539	.054	62	
27 , 28	.440	.054	58	
Air Flow Rate = 27,600 feet/hour				
29	0.0715	0.023	57	
30	.174	"	58	
31	.144	"	57	
32	.119	"	64	
33 , 34	.0753	"	62	
35 , 36	.204	"	60	
37 , 38	.177	"	67	
39 , 40	.157	"	70	
41	.212	"	70	
42	.349	"	70	
43 , 44	.324	"	67	
45	.260	"	62	
46	.461	"	62	
Air Flow Rate = 32,400 feet/hour				
47 , 48	0.145	0.027	57	
49 , 50	.120	"	67	
51	.0520	"	64	
52	.130	"	64	
53 , 54	.251	"	61	
55 , 56	.203	"	72	
57 , 58	.267	"	67	
59 , 60	.330	"	63	
61	.248	"	72	
62	.206	"	70	
63	.203	"	65	

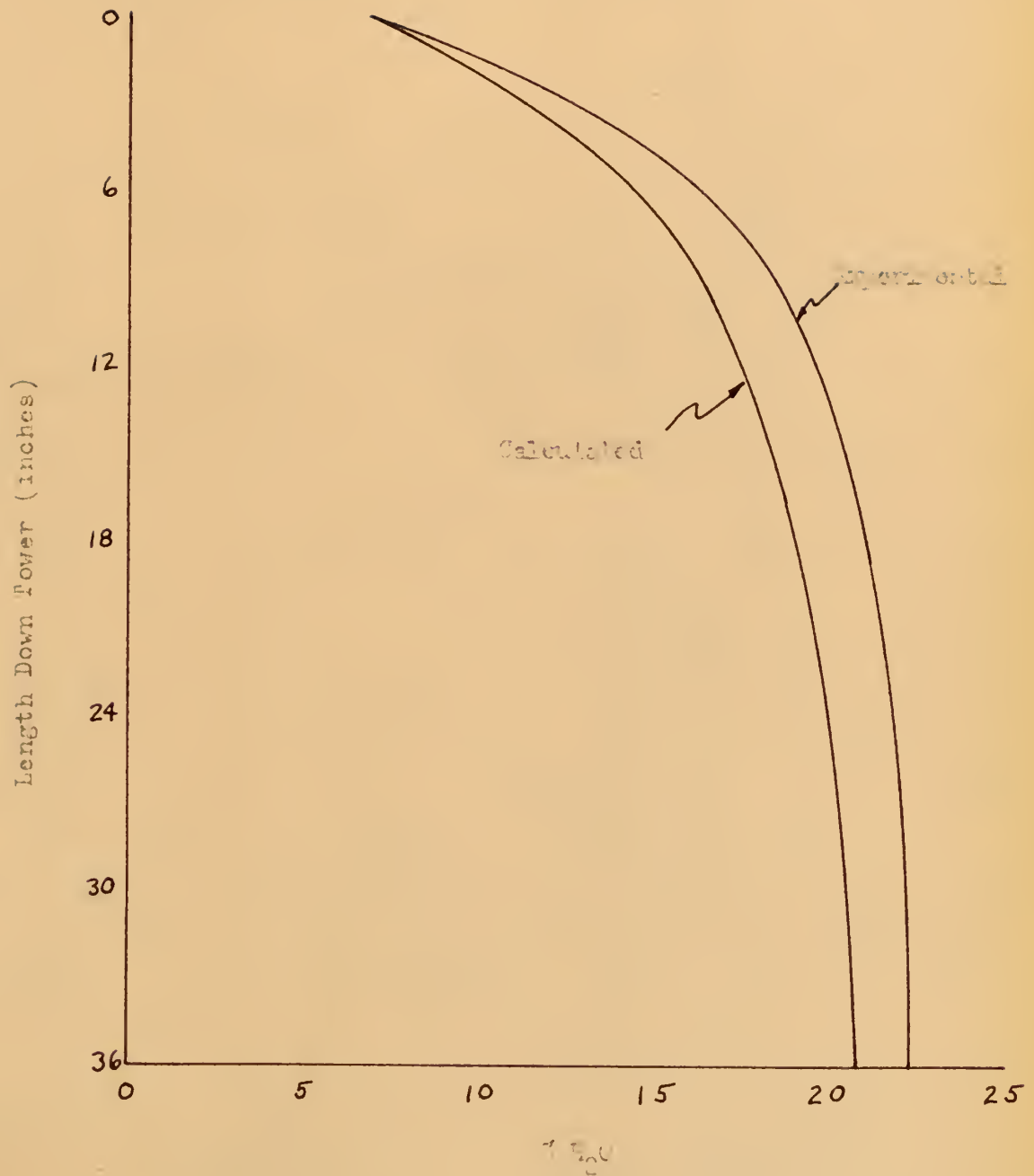
Table 5. Operating conditions for propylene glycol runs.

Air Flow Rate = 18,300 feet/hour						
Run Number	:	Inlet Solution Flow Rate (lbs./ hour)	:	Inlet Concentration (mass fraction water)	:	Relative Humidity (%)
9		0.0958		0.042		48
10 , 11		.116		.043		50
12 , 13		.109		.040		60
14 , 15		.0960		.040		66
16 , 17		.210		.042		66
18 , 19		.185		.043		61
20 , 21		.168		.054		55
22 , 23		.270		.054		49
24		.288		.055		64
25 , 26		.410		.055		63
27 , 28		.360		.055		58
Air Flow Rate = 21,600 feet/hour						
29		0.102		0.015		57
30 , 31		.270		.015		58
32		.267		.015		64
33 , 34		.218		.020		62
35 , 36		.145		.020		60
37 , 38		.123		.028		67
39 , 40		.123		.028		70
41 , 42		.358		.036		70
43 , 44		.367		.036		67
45 , 46		.373		.036		62
Air Flow Rate = 23,400 feet/hour						
47 , 48		0.0701		.015		57
49 , 50		.0536		"		67
51		.133		"		64
52		.0542		"		64
53 , 54		.164		"		60
55 , 56		.118		"		72
57 , 58		.200		"		67
59 , 60		.263		"		63
61 , 62		.231		"		71
63		.206		"		65

EXPLANATION OF PLATE IX

Experimental and calculated concentration profiles for averages
of Runs 12, 13 ethylene glycol.

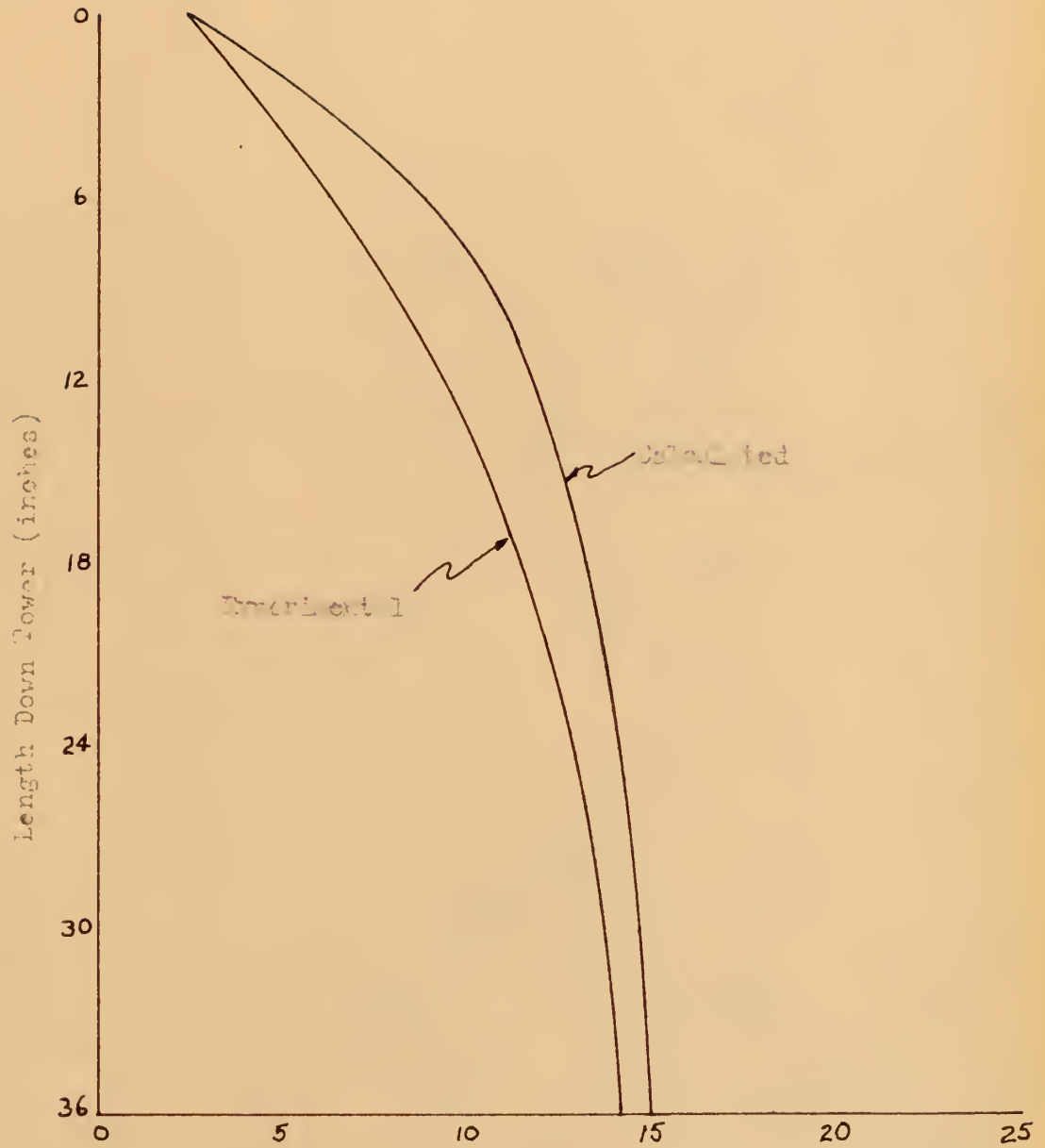
PLATE IX



EXPLANATION OF PLATE X

Experimental and calculated concentration profiles for averages
of Runs 35, 36 ethylene glycol.

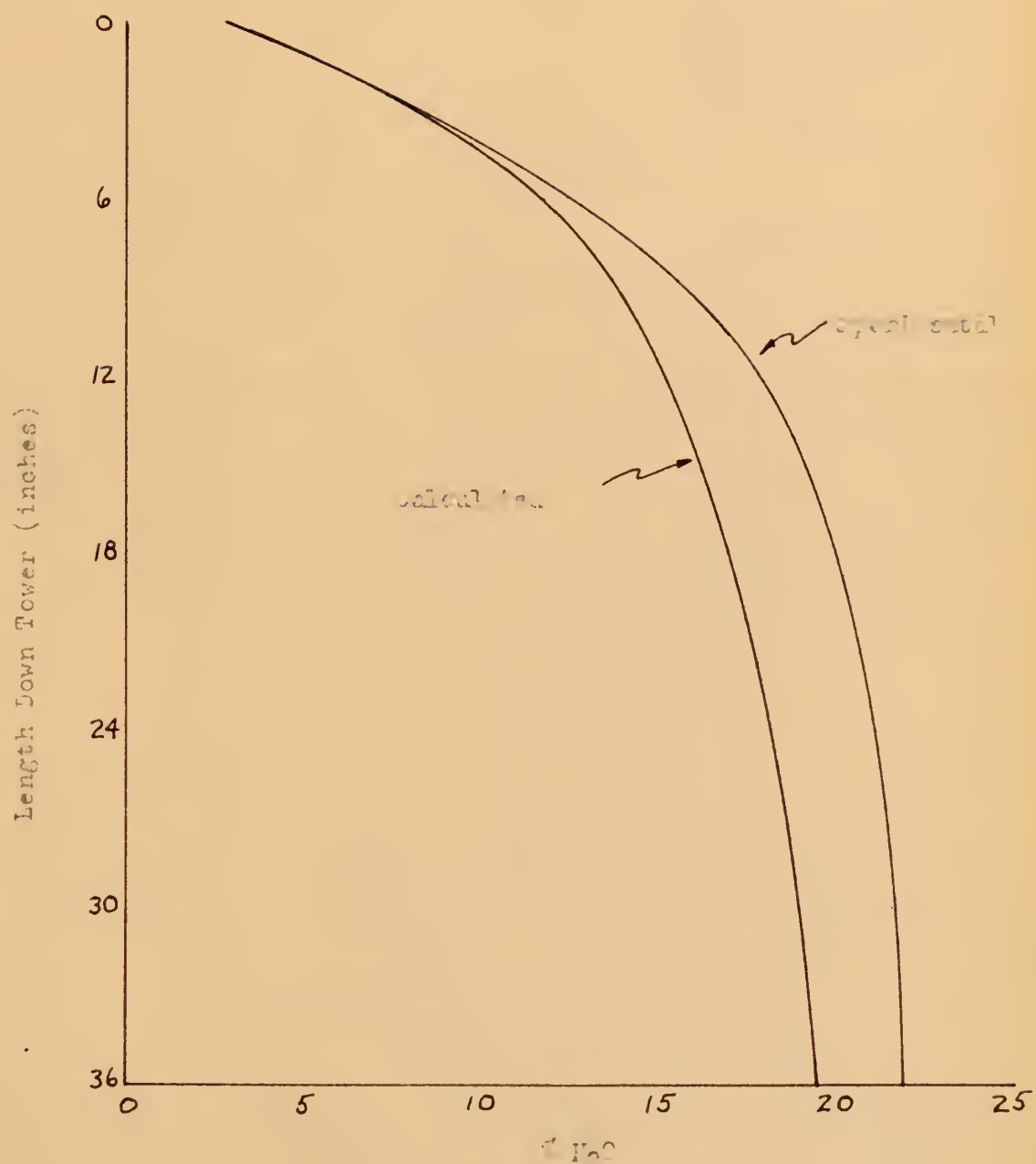
PLATE X



EXPLANATION OF PLATE XI

Experimental and calculated concentration profiles for averages
of Runs 55, 56 ethylene glycol.

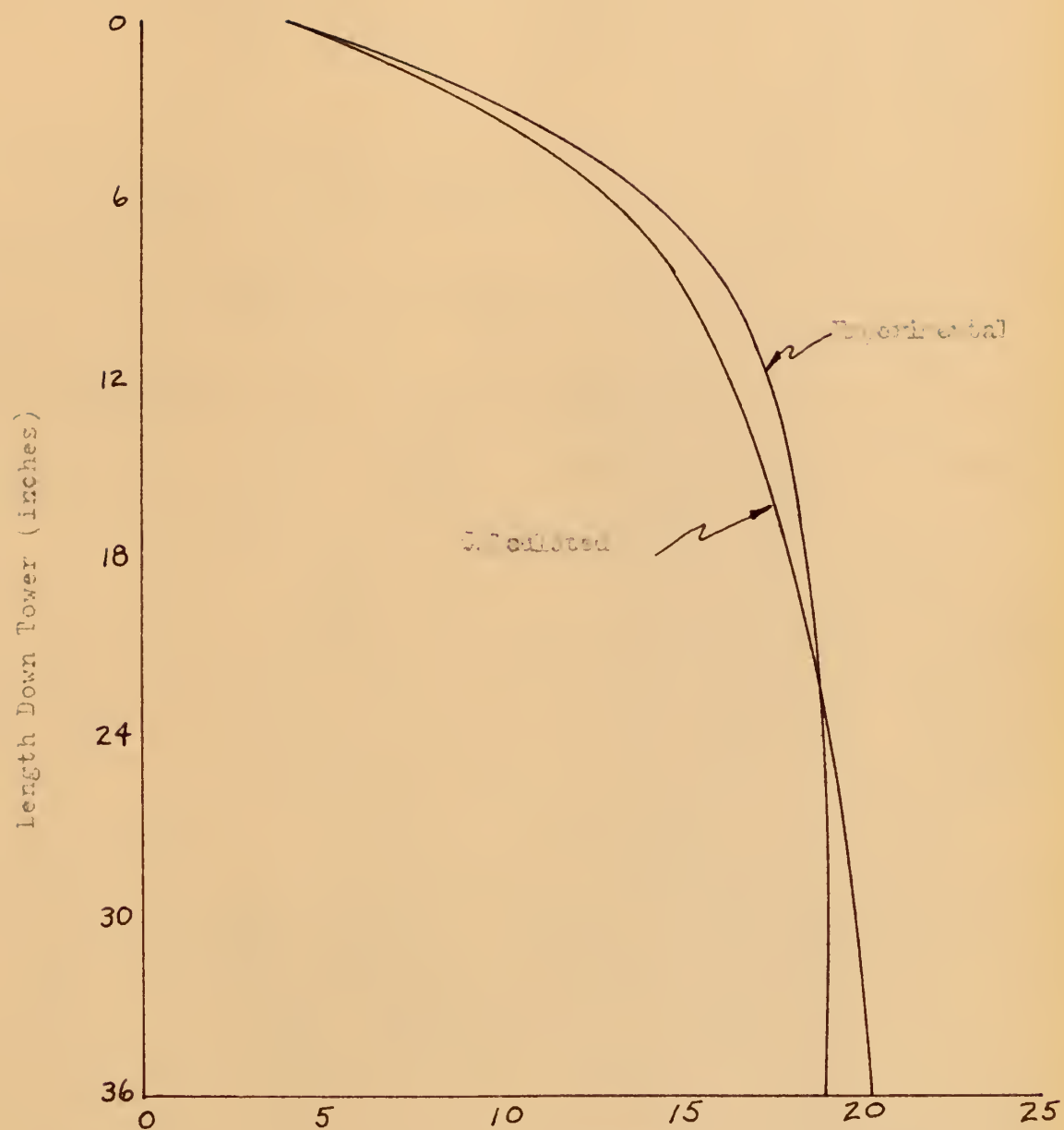
PLATE XI



EXPLANATION OF PLATE XII

Experimental and calculated concentration profiles for averages
of Runs 14, 15 propylene glycol.

PLATE XII

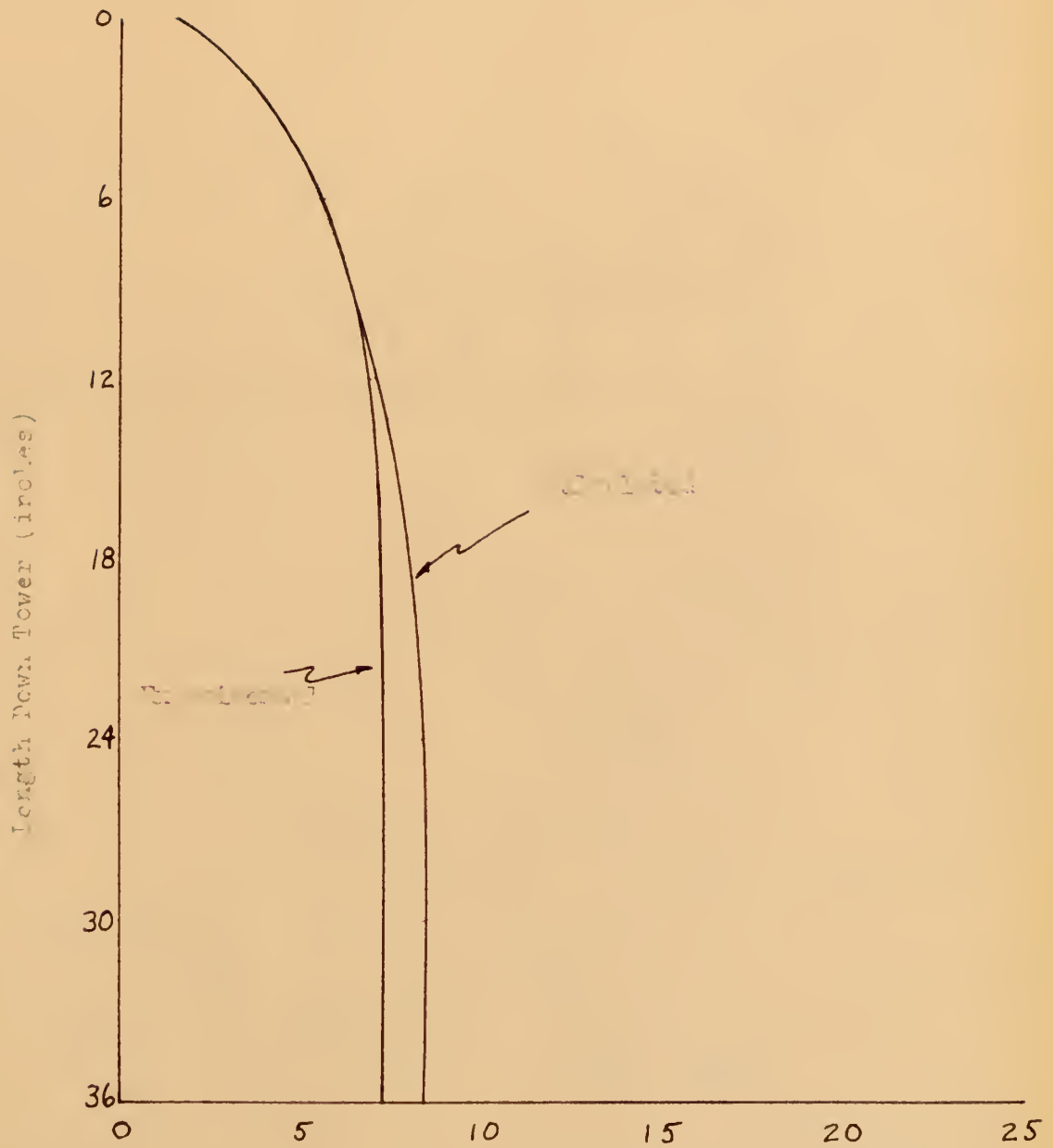


7-165

EXPLANATION OF PLATE XIII

Experimental and calculated concentration profiles for averages
of Runs 30, 31 propylene glycol.

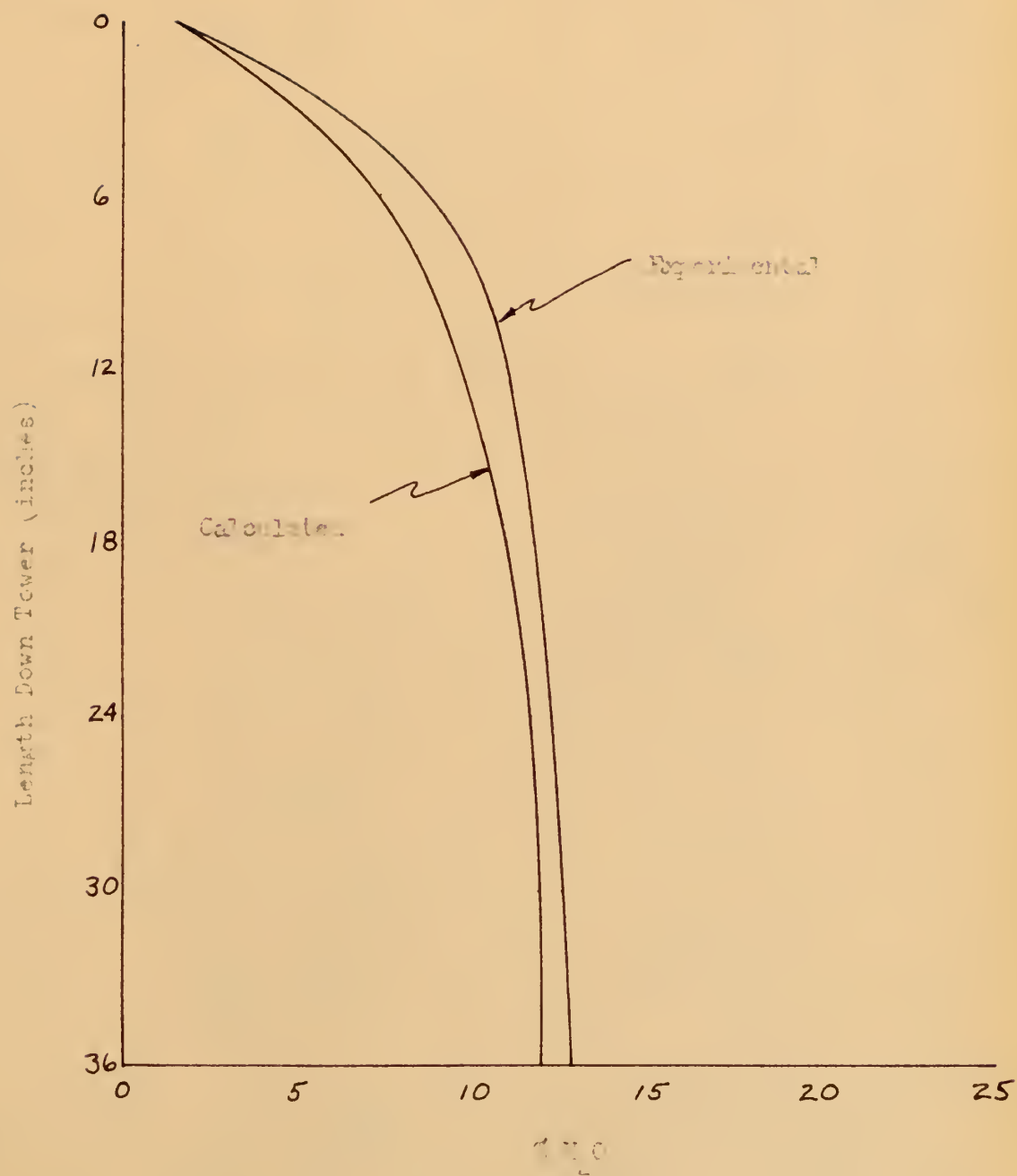
FLAT XIII



EXPLANATION OF PLATE XIV

Experimental and calculated concentration profiles for averages
of Runs 57, 58 propylene glycol.

PLATE XIV



Tables 6 and 7 summarize the pounds per hour of water transferred by each tower under the various operating conditions.

Table 6. Water absorbed, ethylene glycol runs.

Run Number	: Initial Flow Rate : lbs./hr.	: Final Flow Rate : lbs./hr.	: Water Absorbed : lbs./hr.
9	0.0929	0.1012	0.0083
10 , 11	.127	.1381	.0111
12 , 13	.114	.137	.023
14 , 15	.0941	.1218	.0277
16 , 17	.256	.316	.060
18 , 19	.195	.231	.036
20 , 21	.145	.1638	.0188
22 , 23	.302	.3202	.0182
24 , 25	.287	.336	.049
26	.539	.6075	.0685
27 , 28	.440	.488	.048
29	.0715	.0797	.0082
30	.174	.1955	.0215
31	.144	.1601	.0161
32	.199	.1391	.0201
33 , 34	.0753	.0869	.0116
35 , 36	.204	.232	.028
37 , 38	.177	.216	.039
39 , 40	.157	.202	.045
41	.212	.267	.055
42	.349	.433	.084
43 , 44	.324	.390	.066
45	.260	.3035	.0435
46	.461	.535	.074
47 , 48	.145	.160	.015
49 , 50	.120	.1447	.0247
51	.0520	.0648	.0128
52	.130	.152	.022
53 , 54	.251	.283	.032
55 , 56	.203	.252	.049
57 , 58	.267	.317	.050
59 , 60	.330	.376	.046
61	.248	.303	.055
62	.206	.252	.046
63	.203	.252	.049

Table 7. Water absorbed, propylene glycol runs.

Run Number	Initial Flow Rate lbs./hr.	Final Flow Rate lbs./hr.	Water Absorbed lbs./hr.
9	0.0958	0.1025	0.0067
10 , 11	.116	.1225	.0065
12 , 13	.109	.1226	.0138
14 , 15	.0960	.1132	.0172
16 , 17	.210	.2385	.0285
18 , 19	.185	.201	.016
20 , 21	.168	.175	.007
22 , 23	.270	.273	.003
24 , 25	.288	.3082	.0202
26 , 27	.410	.435	.025
28 , 29	.360	.378	.018
30 , 31	.102	.1095	.0075
32 , 33	.270	.287	.017
34 , 35	.267	.2875	.0205
36 , 37	.218	.233	.015
38 , 39	.145	.1568	.0118
40 , 41	.123	.138	.011
42 , 43	.123	.1435	.0205
44 , 45	.358	.389	.031
46 , 47	.367	.396	.029
48 , 49	.373	.396	.023
50 , 51	.0701	.0752	.0051
52 , 53	.0536	.0617	.0081
54 , 55	.133	.1436	.0106
56 , 57	.0542	.0614	.0072
58 , 59	.164	.178	.0140
60 , 61	.118	.1374	.0194
62 , 63	.200	.226	.0260
64 , 65	.263	.2855	.0225
66 , 67	.231	.263	.0320
68 , 69	.206	.225	.0190

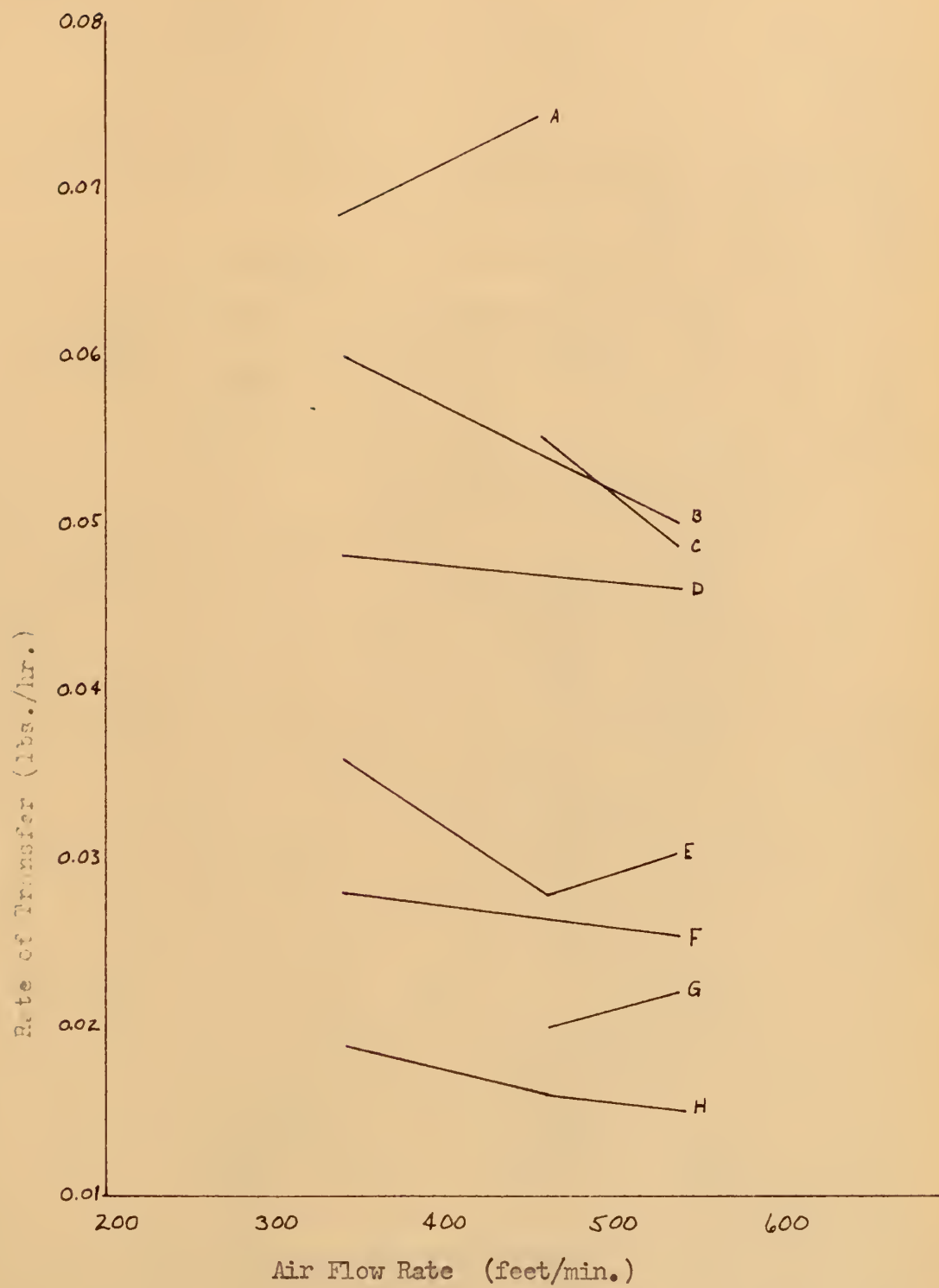
Data from Tables 6 and 7 are plotted in PLATES XV through XX. The data are plotted with two variables held constant, or nearly constant, while the third was varied. No indication of any effect of air flow rate on the rate of transfer at constant relative humidity and liquid flow rate was obtained as the lines on PLATES XV and XVI show. PLATES XVII and XVIII show that the

EXPLANATION OF PLATE XV

Trend lines for the transfer rate for the entire tower versus the air flow rate in feet per minute for the ethylene glycol data. Parameters are constant solution flow rate and constant relative humidity.

- A- Runs 26 and 46.
- B- Runs 16, 17 and 57, 58.
- C- Runs 41 and 55, 56.
- D- Runs 25 and 49, 50.
- E- Runs 19 and 35, 36 and 53.
- F- Runs 14, 15 and 49, 50.
- G- Runs 32 and 52.
- H- Runs 20, 21 and 31 and 47, 48.

PLATE XV



EXPLANATION OF PLATE XVI

Trend lines for transfer rate for entire tower versus air flow rate in feet per minute for propylene glycol data. Parameters are constant solution flow rate and constant relative humidity.

A- Runs 16, 17 and 57, 58.

B- Runs 26 and 45, 46.

C- Runs 24 and 32 and 59, 60.

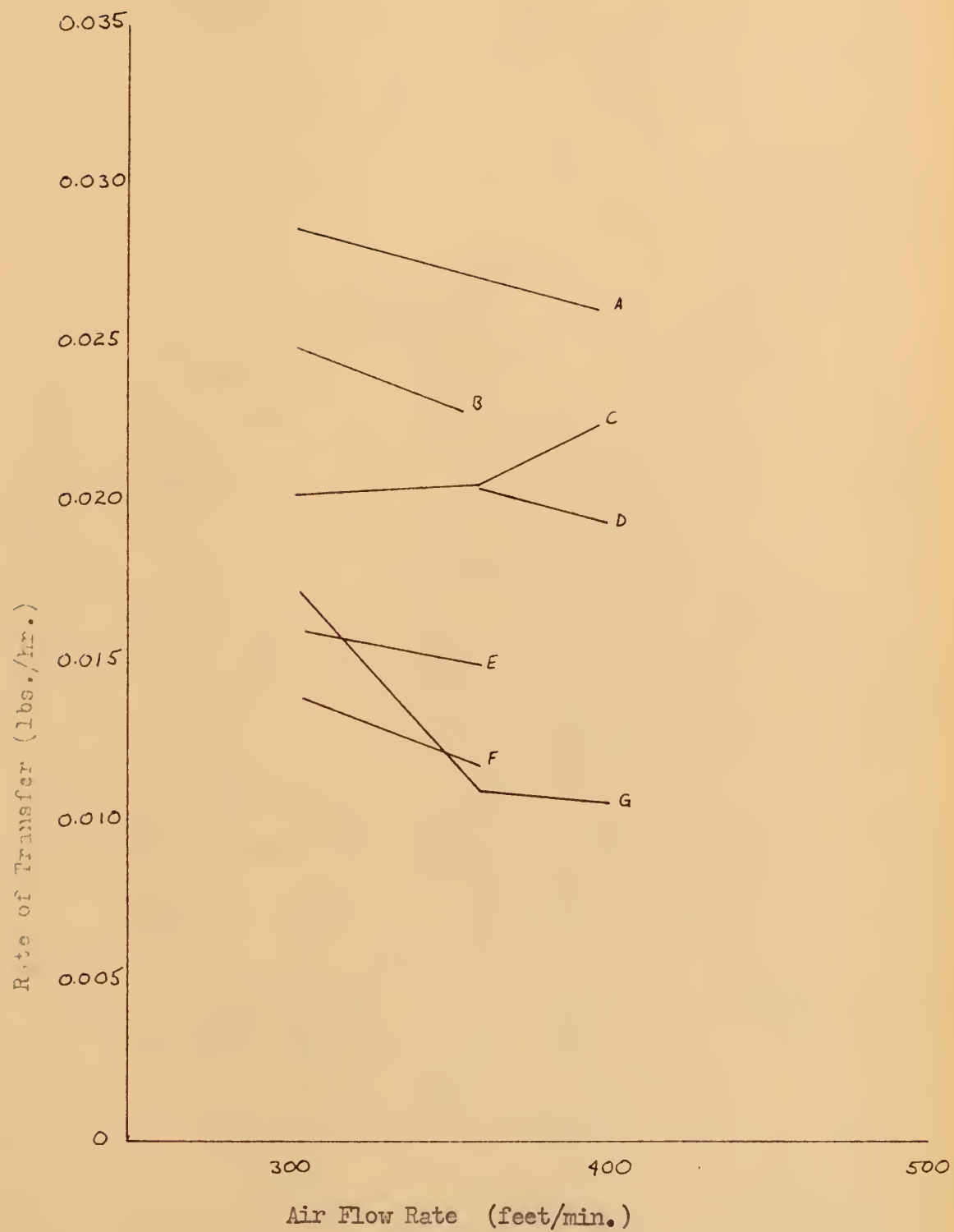
D- Runs 39, 40 and 55, 56.

E- Runs 18, 19 and 33, 34.

F- Runs 12, 13 and 35, 36.

G- Runs 14, 15 and 37, 38 and 51.

PLATE XVI



EXPLANATION OF PLATE XVII

Trend lines for transfer rate for the entire tower versus relative humidity of the main air stream for ethylene glycol data. Parameters are constant air flow rate and constant solution flow rate.

A- Runs 16, 17 and 22, 23 and 24, 25.

B- Runs 57, 58 and 61.

C- Runs 53, 54 and 55, 56 and 63.

D- Runs 35, 36 and 37, 38 and 39, 40.

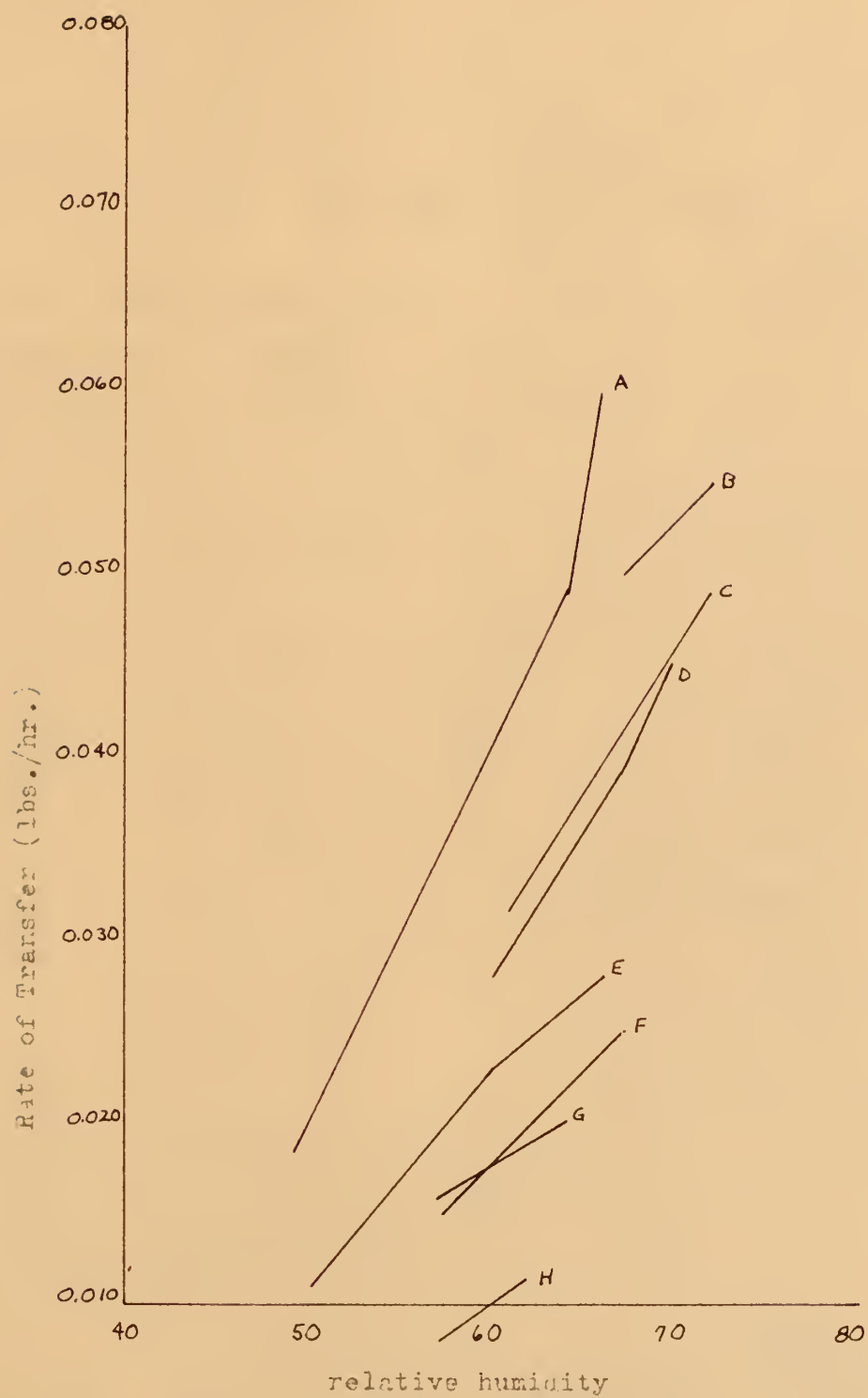
E- Runs 10, 11 and 12, 13 and 14, 15.

F- Runs 47, 48 and 49, 50 and 52.

G- Runs 31 and 32.

H- Runs 29 and 33, 34.

PLATE XVII

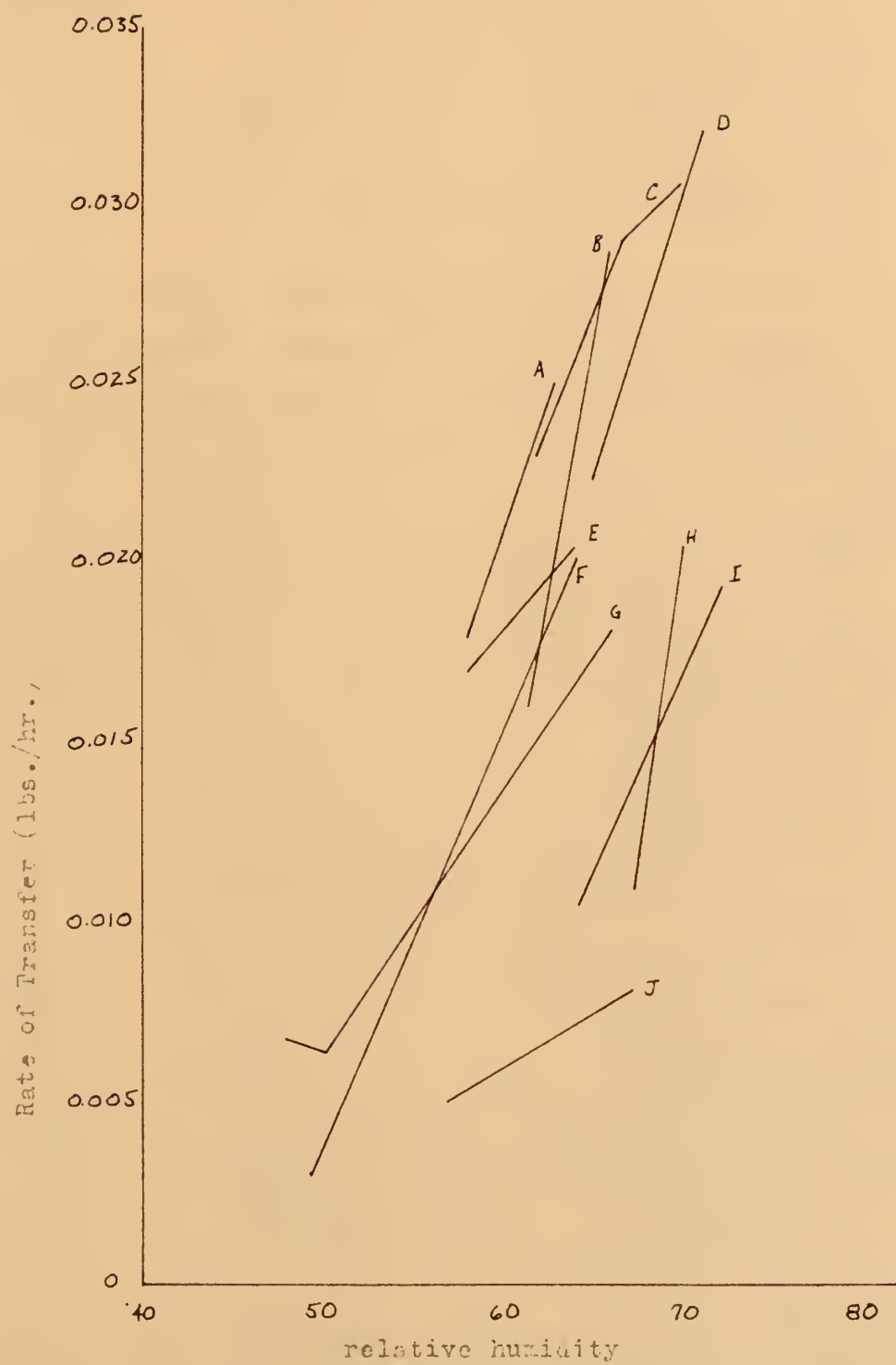


EXPLANATION OF PLATE XVIII

Trend lines for transfer rate for the entire tower versus relative humidity of the main air stream for propylene glycol data. Parameters are constant air flow rate and constant solution flow rate.

- A- 25, 26 and 27, 28.
- B- 16, 17 and 18, 19.
- C- 41, 42 and 43, 44 and 45, 46.
- D- 59, 60 and 61, 62.
- E- 30, 31 and 32.
- F- 22, 23 and 24.
- G- 9 and 10, 11 and 12, 13 and 14, 15.
- H- 37, 38 and 39, 40.
- I- 51 and 55, 56.
- J- 47, 48 and 49, 50 and 52.

PLATE XVIII



EXPLANATION OF PLATE XIX

Trend lines for the rate of transfer for the entire tower versus the solution flow rate for the ethylene glycol data. Parameters are constant air flow rate and constant relative humidity.

A- 39, 40 and 41, 42.

B- 14, 15 and 16, 17.

C- 55, 56 and 61.

D- 37, 38 and 43, 44.

E- 49, 50 and 57, 58.

F- 33, 34 and 45, 46.

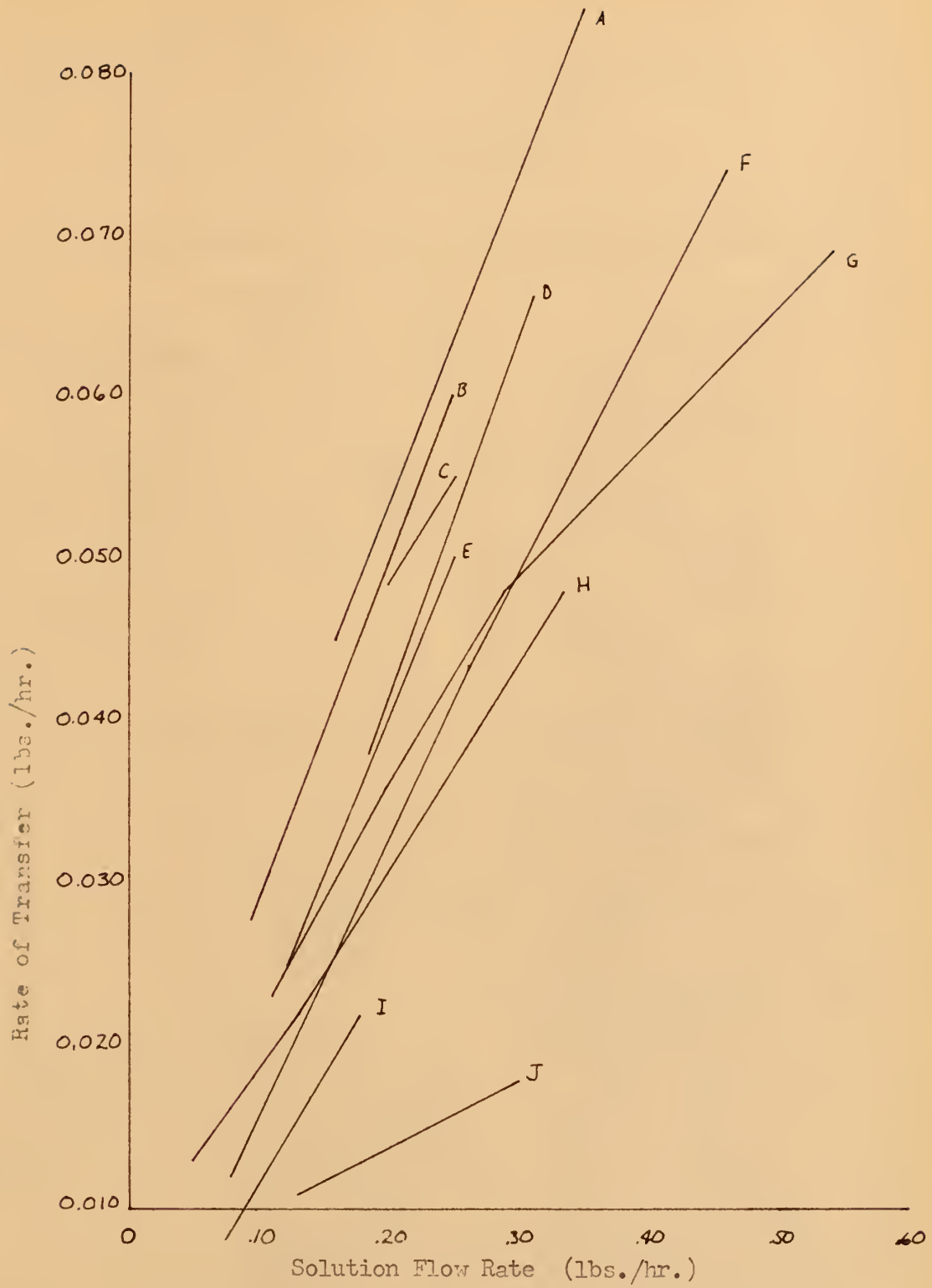
G- 12, 13 and 18, 19 and 24, 25 and 26.

H- 51 and 52 and 59, 60.

I- 29 and 30 and 31.

J- 10, 11 and 22, 23.

PLATE XIX



EXPLANATION OF PLATE XX

Trend lines for the rate of transfer for the entire tower versus the solution flow rate for the propylene glycol data. Parameters are constant air flow rate and constant relative humidity.

A- 55, 56 and 61, 62.

B- 14, 15 and 16, 17.

C- 49, 50 and 57, 58.

D- 39, 40 and 41, 42.

E- 37, 38 and 43, 44.

F- 51 and 52 and 59, 60 and 63.

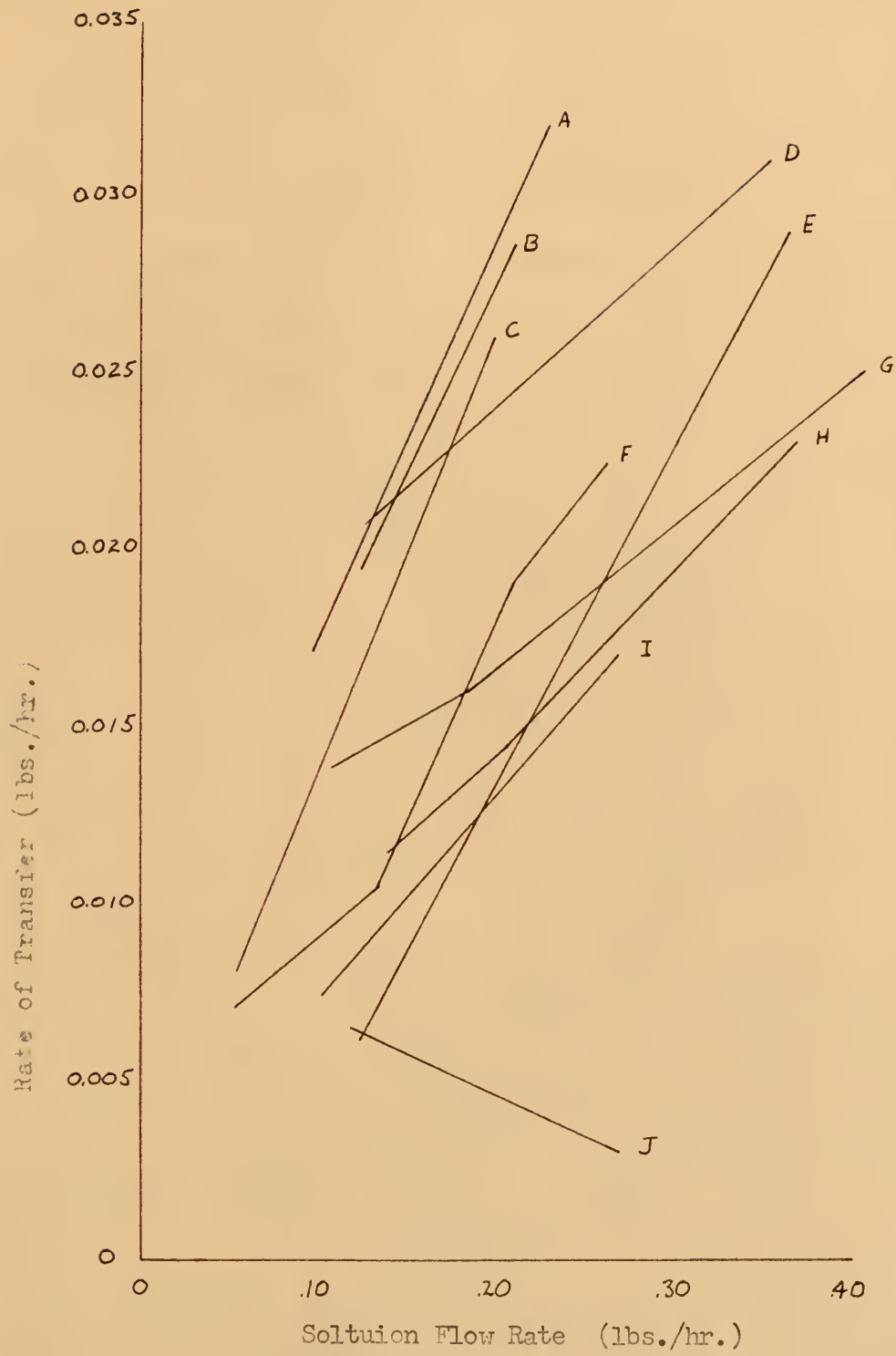
G- 12, 13 and 18, 19 and 25, 26.

H- 33, 34 and 35, 36 and 45, 46.

I- 29 and 30, 31.

J- 10, 11 and 22, 23.

PLATE XX



water vapor concentration in the main air stream does materially affect the transfer rate when the air flow rate and glycol solution flow rate are constant. PLATES XIX and XX show the glycol solution flow rate to be important in the transfer rate when air flow rate and relative humidity are constant.

Calculated Results

The outlet water concentrations and final flow rates calculated by the mathematical model previously developed are given in Tables 8 and 9. Representative curves of the calculated concentrations at various levels in the tower are also shown in PLATES IX through XIV. The curves show that the calculated profiles were similar to the experimental profiles.

Comparison of Experimental and Calculated Results

From Tables 6, 7, 8, and 9, the experimental and calculated water transfer rates were compared. Table 10 shows the comparisons by presenting the experimental as a per cent of the calculated transfer rates. PLATES XXI and XXII are plots of the per cent of calculated transfer rates versus flow rate of inlet solution in pounds per hour for ethylene and propylene glycol solutions, respectively.

A linear regression analysis, (5), was run on each of the sets of data points. The results are summarized in Table 11.

Table 8. Calculated transfer rate, ethylene glycol runs.

Run Number	Initial Flow lbs./hr.	Final Conc. % H ₂ O	Final Flow lbs./hr.	Water Transferred lbs./hr.
	0.0929	16.9	0.1045	0.0116
10 , 9	.127	16.3	.1420	.0150
12 , 11	.114	20.7	.1342	.0202
14 , 13	.0941	24.4	.1162	.0221
16 , 15	.256	17.2	.2887	.0327
18 , 17	.195	17.3	.2215	.0265
20 , 19	.145	17.0	.1651	.0201
22 , 21	.302	11.5	.3228	.0208
24 , 23	.287	15.2	.3200	.0330
	.539	11.4	.5757	.0367
27 , 26	.440	11.6	.4711	.0311
	.0715	21.2	.0887	.0172
	.174	15.6	.2014	.0274
	.144	16.7	.1689	.0249
	.119	20.9	.1470	.0280
33 , 32	.0753	23.3	.0959	.0206
35 , 34	.204	15.0	.2345	.0305
37 , 36	.177	18.5	.2122	.0352
39 , 38	.157	20.7	.1935	.0365
	.212	17.8	.2521	.0401
	.349	13.5	.3941	.0451
43 , 42	.324	13.3	.3652	.0412
	.260	13.7	.2943	.0343
	.461	10.0	.5007	.0397
47 , 46	.145	16.9	.1697	.0247
49 , 48	.120	22.3	.1502	.0302
	.0520	26.1	.5365	.0165
	.130	20.4	.1589	.0289
53 , 52	.251	14.1	.2842	.0332
55 , 54	.203	19.3	.2448	.0418
57 , 56	.267	15.3	.3066	.0396
59 , 58	.330	12.7	.3676	.0376
	.248	17.4	.2922	.0442
	.206	18.5	.2459	.0399
63 , 62	.203	17.0	.2379	.0349

Table 9. Calculated transfer rate, propylene glycol runs.

Run Number	Initial Flow lbs./hr.	Final Conc. % H ₂ O	Final Flow lbs./hr.	Water Transferred lbs./hr.
9	0.0958	12.1	0.1045	0.0087
10 , 11	.116	11.9	.1260	.0100
12 , 13	.109	15.9	.1244	.0154
14 , 15	.0960	20.2	.1154	.0194
16 , 17	.210	13.4	.2322	.0222
18 , 19	.185	12.7	.2028	.0178
20 , 21	.168	12.3	.1812	.0132
22 , 23	.270	9.4	.2819	.0119
24	.288	12.2	.3099	.0219
25 , 26	.410	10.7	.4336	.0236
27 , 28	.360	10.2	.3788	.0188
29	.102	13.6	.1163	.0143
30 , 31	.270	7.9	.2889	.0189
32	.267	9.3	.2900	.0230
33 , 34	.218	10.3	.2381	.0201
35 , 36	.145	12.3	.1621	.0171
37 , 38	.123	17.5	.1449	.0219
39 , 40	.123	19.2	.1479	.0249
41 , 42	.358	11.1	.3881	.0301
43 , 44	.367	10.3	.3944	.0274
45 , 46	.373	9.3	.3963	.0233
47 , 48	.0701	16.9	.0831	.0130
49 , 50	.0536	26.5	.0718	.0182
51	.133	14.4	.1530	.0200
52	.0542	24.9	.0702	.0160
53 , 54	.164	11.1	.1817	.0177
55 , 56	.118	20.2	.1456	.0276
57 , 58	.200	12.1	.2240	.0240
59 , 60	.263	9.2	.2852	.0222
61 , 62	.231	12.4	.2597	.0287
63	.206	11.2	.2284	.0224

Table 10. Ratio of experimental to calculated transfer rate as per cent for ethylene glycol and propylene glycol.

Ethylene Glycol			:	Propylene Glycol		
Run No.	F. R.*	Ratio	:	Run No.	F. R.*	Ratio
9	0.0929	71.5%		9	0.0958	78.1%
10 , 11	.127	74.5		10 , 11	.116	65.0
12 , 13	.114	114.4		12 , 13	.109	89.5
14 , 15	.0941	125.0		14 , 15	.096	88.9
16 , 17	.256	183.0		16 , 17	.210	128.5
18 , 19	.195	136.0		18 , 19	.185	90.0
20 , 21	.145	93.5		20 , 21	.168	52.9
22 , 23	.302	87.5		22 , 23	.270	25.2
24 , 25	.287	148.0		24 , 25	.288	92.4
26	.539	187.0		25 , 26	.410	106.0
27 , 28	.440	154.0		27 , 28	.360	95.8
29	.0715	47.8		29	.102	52.5
30	.174	78.5		30 , 31	.270	90.1
31	.144	64.8		31 , 32	.267	89.2
32	.119	71.8		33 , 34	.218	74.3
33 , 34	.0753	56.3		35 , 36	.145	69.0
35 , 36	.204	91.8		37 , 38	.123	50.2
37 , 38	.177	111.0		39 , 40	.123	82.4
39 , 40	.157	123.0		41 , 42	.358	103.0
41	.212	137.0		43 , 44	.367	106.0
42	.349	186.0		45 , 46	.373	98.6
43 , 44	.324	161.0		47 , 48	.0701	39.3
45	.260	126.5		49 , 50	.0536	45.5
46	.461	186.0		51	.133	53.0
47 , 48	.145	60.8		52	.0542	44.9
49 , 50	.120	81.9		53 , 54	.164	79.0
51	.052	77.6		55 , 56	.118	70.3
52	.130	76.0		57 , 58	.200	108.0
53 , 54	.251	96.5		59 , 60	.263	101.0
55 , 56	.203	117.0		61 , 62	.231	111.5
57 , 58	.267	126.0		63	.206	85.0
59 , 60	.330	122.0				
61	.248	123.5				
62	.206	115.5				
63	.203	139.0				

* Inlet solution flow rate (lbs./hr.).

Table 11. Regression analysis of correlated results.

Glycol	: Least Squares : Equation	: Correlation : Coefficient	: Correlation : Coefficient Squared
Ethylene	$Y = 55 \neq 270X$	0.78	0.62
Propylene	$Y = 52 \neq 140X$	0.58	0.34

The average per cent ratio of experimental to calculated results for the ethylene data was 112.9 per cent and for the propylene glycol data was 79.5 per cent. The average for the ethylene glycol data and propylene glycol data together was 97.2 per cent.

DISCUSSION

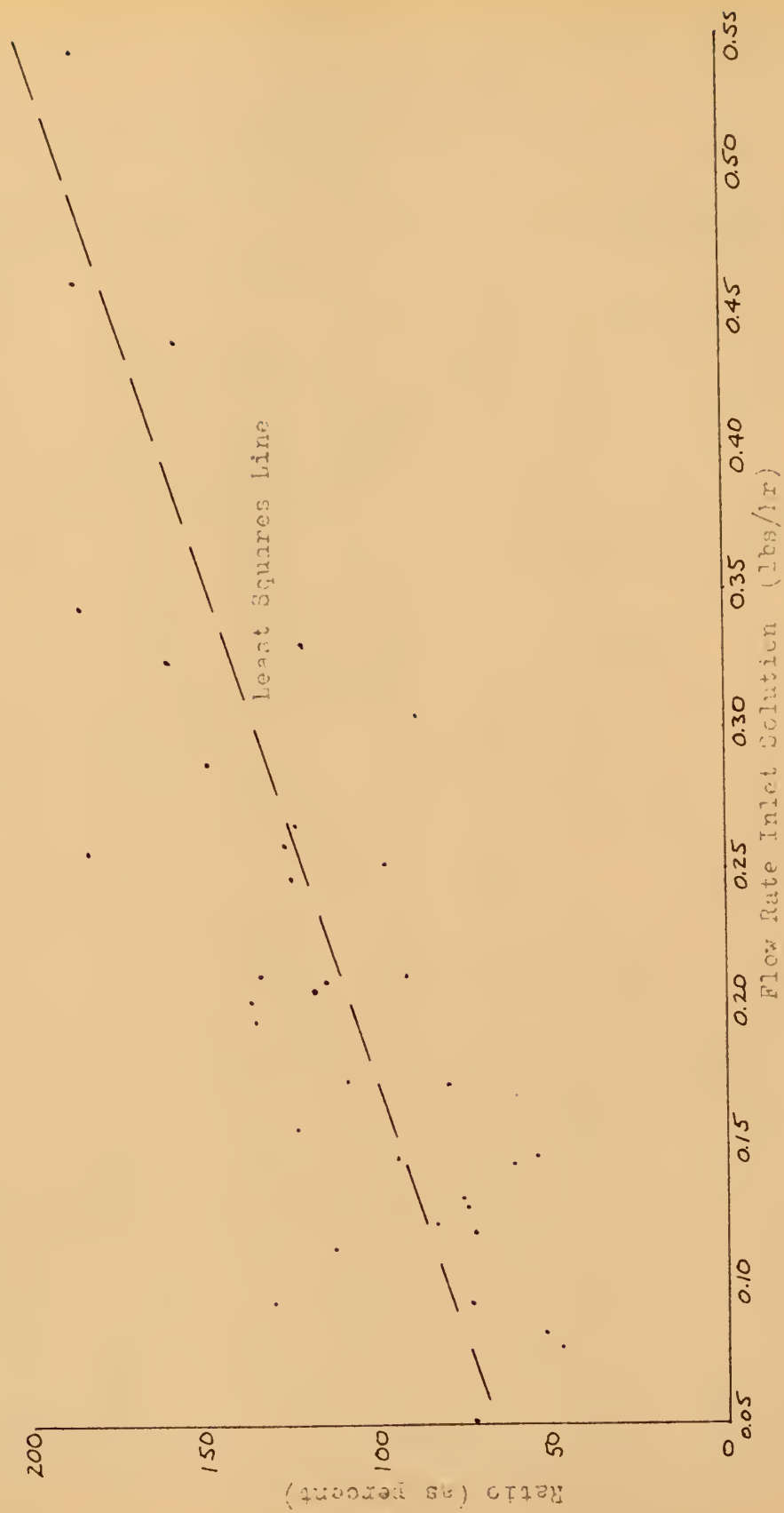
In equation (5) the assumptions were that the density, viscosity, and diffusivity through the air stream were constant. Sample Calculations A-1 in the Appendix show that the magnitude of the changes in viscosity and density were small. The diffusivity should also have been constant since the rates of mass transfer were low and the main air stream concentration would therefore remain essentially constant.

Equation (5) also required the liquid concentration in any horizontal plane to be constant. PLATE XXIV in the Appendix immediately revealed that the concentration was not constant. However, inspection of PLATE XXIV in the Appendix revealed that the concentration profile was symmetrical on a given horizontal traverse. Also, a dye trace of the liquid flow on the propylene

EXPLANATION OF PLATE XXI

Plot of the ratio of experimental flow rates to calculated flow rates, as per cent, versus inlet solution flow rate for the ethylene glycol data. The equation for the least squares line is $y = 55 + 270x$.

PLATE XXI



EXPLANATION OF PLATE XXII

Plot of the ratio of experimental flow rates to calculated flow rates, as per cent, versus inlet solution flow rate for the propylene glycol data. The equation for the least squares line is $y = 52 + 140x$.

PLATE XXII



tower, PLATE XXIII, showed a somewhat symmetrical distribution. Therefore, the requirement of constant concentration in a horizontal plane could probably be obtained with a much wider plate, since the wider plate would tend to eliminate or minimize edge effects on the vertical liquid velocity distributions which were created by the size of the equipment used in gathering these data.

In the original integration of equation (6), it was assumed that the velocity profile in a vertical plane perpendicular to the face of the plate took the shape of a parabola. A parabolic profile is unlikely within the cloth covered surface because skin friction effects exist throughout all regions of the liquid film. A profile approaching plug flow is more likely to describe the actual velocity distribution.

In equation (8), Johnstone and Pigford showed K_2 equal to 0.7857 and K_3 equal to 5.121 for parabolic velocity distribution. Since the velocity distribution was not known in this experiment, the constants were changed empirically to give the best fit of the data. The new constants were K_2 equal to 0.882 and K_3 equal to 7.65. The method of fitting the constants is shown in Sample Calculations A-5, Appendix.

Also, it was assumed in equation (8) that the absorbed water never reached the inside of the liquid film. The assumption means that the concentration of the inside face of the liquid film was the initial concentration for the entire length of the tower. This assumption could have been invalid in the

EXPLANATION OF PLATE XXIII

Propylene glycol tower dye trace with time.

PLATE XXIII

A

After 5 Minutes



E

Trace Complete



Note: Given sufficient time E would become completely covered with dye.

upper sections of the tower, but was probably valid in the upper sections of the tower, where the majority of the mass transfer took place.

The constant, α , in equation (9) was taken as about that for alcohols of the same molecular weight as ethylene and propylene glycol, since no experimental values for this parameter were available for the glycols (11).

Table 1 showed distinctly that a liquid film could be made thicker with the aid of surface cover than would be possible by the normal process of running a liquid down a vertical flat plate. The advantage of the thicker liquid film is that it allows greater time of contact between the passing gases and the liquid, and this in turn results in a greater final concentration in the liquid than would be possible with a plain vertical flat plate. The higher concentration of the water makes the separation of the water and glycol simpler and less costly.

Tables 4 and 5 show that the originally desired nested data table was not achieved. The reasons were that the relative humidity could not be returned exactly to a previous level and the inlet solution feed rates could not be duplicated.

PLATES XV and XVI show trends in a direction opposite to that predicted by equation (5). The range of flat plate Reynolds Numbers, $(\frac{\rho V \infty}{\mu})$, were less than 10^{-5} , as shown in Table 12. Therefore, all air flow is in the accepted laminar range (1), and within the assumptions of equation (5).

PLATES XV and XVI indicate that the velocity measurements were incorrect. However, since the transfer rate varies directly

as the square root of the velocity, a slight error in the velocity measurement should not have had a great effect.

Table 12. Flat plate Reynolds Numbers.

Data	:	Air Flow Rate	:	N_{RE}
Ethylene (High)		32,400 ft./hr.		26,100
Ethylene (Low)		20,400		16,400
Propylene (High)		23,400		18,800
Propylene (Low)		18,300		14,700

The trends shown in PLATES XVII and XVIII were expected since the rate of mass transfer should increase with relative humidity.

PLATES XIX and XX indicate that the amount of water transferred was directly proportional to the solution flow rate. The differences in the slopes of some of the lines is probably due to sampling error.

The relationships between the error and the glycol solution flow rates established in PLATES XXI and XXII both appear plausible. At low solution flow rates the pores in the corduroy cloth may not have all been filled, and these voids would have offered additional resistance to mass transfer. Visual inspection of the towers during operation indicated that there was no glycol solution on the outer surface of the cloth at flow rates below approximately 0.15 pounds per hour for either glycol. This lack of surface solution could account for the experimental values being below the theoretical. The lack of solution at the

surface of the cloth would not be reflected in equations (5) and (7) since the average of all the measured film thicknesses was used for all flow rates.

At the higher flow rates, where the solution flowed visibly on the surface, a different phenomena may have been encountered. As the solution flowed over the surface, it would have to flow over the ridges of the corduroy cloth and an artificial turbulence could have been induced. The induced turbulence would have increased the rate of diffusion of water into the liquid and subsequently increased the rate of mass transfer.

Plots of the ratio of experimental to calculated transfer rates against relative humidity and against air flow rate did not show any correlation. A multiple correlation was not performed because of the known non-linearity of the system. No knowledge of the regression equations was available.

PLATES XXI and XXII may also indicate the flow rate at which the film thickness was exactly 0.089 cm., that was used in all calculations. From PLATE XXI, the trend line for ethylene glycol crossed the 100 per cent line at approximately 0.17 pounds per hour. PLATE XXII showed the trend line for propylene glycol crossing the 100 per cent line at 0.36 pounds per hour.

CONCLUSIONS

It was concluded from the study that the liquid hold-up on a flat plate column can be made to be independent of the feed rate of the liquid to the column.

The use of the boundary layer mass transfer equation (5),

and the liquid diffusion equation (7), combined with an iteration procedure adequately described the mass transfer for the system studied.

RECOMMENDATIONS

It is recommended that, (1) a study of the fluid flow on flat plates and other geometric shapes covered with hold-up media be made and, (2) the work with the present system be extended to cover mass transfer to liquids other than glycols to test the applicability of the mathematical procedures in this thesis.

ACKNOWLEDGMENTS

Early experimental work on this project was performed by Richard Livingston, under the direction of Assistant Professor Raymond C. Hall. Much credit is due Mr. Livingston for his original work with the experimental equipment design and the refractometer calibration curve.

The understanding, patience, and experience of Professor Hall is acknowledged. Without Professor Hall's direction and interest the project would not have been completed.

Acknowledgment is given to Dr. William H. Honstead, Professor and Head of the Chemical Engineering Department, whose initial co-operation made this work possible.

The funds for this project were provided by the Agricultural Experiment Station of Kansas State University.

TABLE OF NOMENCLATURE

Letters

C_v = concentration of water in air, $\frac{\text{lb-moles}}{\text{cubic foot}}$.

C_L = concentration of water in solution, $\frac{\text{lbs. water}}{\text{lb. solution}}$.

D = diffusivity of water vapor in air, $\frac{\text{ft.}^2}{\text{hr.}}$.

D_L = diffusivity of water in glycol solution, $\frac{\text{ft.}^2}{\text{hr.}}$.

ρ = density lbs./cubic foot.

μ = lbs./foot-hour or centipoise.

θ = time, hours.

Y = liquid film thickness, feet.

T = temperature, $^{\circ}\text{K}$

V = specific volume ml/g-mole.

v = velocity feet/hour.

N = moles per hour transferred.

Γ = mass flow rate, $\frac{\text{lbs.}}{\text{ft.-hr.}}$.

P = dimensionless group.

Subscripts

k = kth increment.

∞ = refers to bulk air.

x = refers to x direction.

y = refers to y direction.

Ave = average concentration (material balance).

i = refers to interface of liquid and vapor.

K = constants.

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APPENDIX

Tables

Table A-1. Temperature-relative humidity calibration of Bristol recorder.

Run No. :	Dry Bulb* °C.	Wet Bulb* °C.	Relative Humidity :	Bristol Temp. °F. :	Bristol Rel. Humidity
1	25.0	19.4	57%	78	57
2	23.8	16.6	47	76	47
3	26.6	19.4	51	81	51

* The mercury thermometers used to calibrate the Bristol recorder were tested in an ice bath and found to read 0.2° C. high at 0° C.

Table A-2. Comparison of "Inside" sample and surface sample.

Run No. :	Inside Sample (%H ₂ O)	Surface Sample (%H ₂ O)	Difference (%H ₂ O)
1	15.8	14.8	+ 1.0
2	10.5	10.8	- 0.3
3	10.7	10.8	- 0.1
4	7.3	7.0	+ 0.3
5	19.7	19.5	+ 0.2

Table A-3. Refractive index versus time.

Run No. :	Instantaneous Refractive Index	One Minute Refractive Index	Two Minute Refractive Index
12E	1.4232	1.4232	1.4232
16E	1.4073	1.4172	1.4172
12P	1.4204	1.4204	1.4205
16P	1.4166	1.4165	1.4166

Table A-4. Density of glycol-water solutions at 80° F. (7).

Ethylene*		:	Propylene**	
% H ₂ O	:		% H ₂ O	:
0	1.108		0	1.0330
5	1.105		5	1.0350
10	1.101		10	1.0364
15	1.098		15	1.0376
20	1.093		20	1.0382
25	1.088		25	1.0388
30	1.083		30	1.0390

* Ethylene glycol solution density used in all calculations was 1.096.

** Propylene glycol solution density used in all calculations was 1.035.

Table A-5. Traverse sample analysis at various lengths.

Run No.	:	Length	:	East* (%H ₂ O)	:	Middle (%H ₂ O)	:	West (%H ₂ O)
9		6		11.8		11.2		13.5
12		6		16.8		16.0		17.6
14		6		21.8		20.2		21.8
16		6		13.8		11.2		14.8
18		6		12.9		11.3		14.7
24		6		12.6		8.8		11.3
26		6		10.5		6.8		9.1
13		12		20.5		19.4		20.6
15		12		25.6		24.3		25.4
17		12		17.7		14.8		18.0
20		12		15.3		14.7		14.6
23		12		9.0		6.9		8.8
12		6		12.8		10.3		13.2
14		6		15.3		11.4		17.3
16		6		17.5		8.8		14.8
18		6		12.1		8.5		11.3
22		6		6.1		6.0		6.5
13		12		16.3		12.3		16.4
15		12		18.8		14.7		18.8
17		12		15.6		11.7		16.0
20		12		10.6		9.1		10.6
23		12		6.6		5.9		6.3

* East sample taken $\frac{1}{2}$ inch from East edge.

Middle sample taken in middle (3 inches from East edge).

West sample taken $\frac{1}{2}$ inch from West edge.

Table A-6. Determination of sample location across plate.

Average of Ethylene Glycol	6 inch East = 14.3% H ₂ O
	6 inch Middle = 12.2
	6 inch West = 14.7
Average of Ethylene Glycol	12 inch East = 17.6
	12 inch Middle = 16.0
	12 inch West = 17.5
Average of Propylene Glycol	6 inch East = 12.8
	6 inch Middle = 9.0
	6 inch West = 12.6
Average of Propylene Glycol	12 inch East = 13.6
	12 inch Middle = 10.8
	12 inch West = 13.6

For 6 inch Ethylene:

Extension to edges of tower gives concentrations of:

East = 14.8% West = 15.2%

Area Under Curve = $1440 - 134 = 1306$ squares

Concentration that would give same area:

$$\frac{1306}{48} = 13.6\%$$

The 13.6% corresponds to 1.5 inches from the East edge of the tower.

Similarly, 12 inch Ethylene = 1.2 inches

6 inch Propylene = 2.7 inches

12 inch Propylene = 2.0 inches

Sample points 18 inch, 24 inch, and 30 inch were taken at the same distance from East edge of tower as the 12 inch sample.

Table A-7. IBM 650 Input - Output Format.

Word :	Input	:	Output
1	Air Flow Rate (feet/min.)		Identification*
2	Solution Flow Rate (lbs./hr.)		6 inch concentration
3	Initial Conc. (mass fraction)		12 inch concentration
4	Relative Humidity (as a fraction)		18 inch concentration
5	blank		24 inch concentration
6	"		30 inch concentration
7	"		36 inch concentration
8	"		Total lbs. water absorbed

* In identification, digits 1-3 are digits 1-3 from input word 1, digits 4-6 are digits 1-3 from word 2 input, digits 7 & 8 are digits 1 & 2 from word 3 input, and digits 9 & 10 are digits 1 & 2 from word 4 input.

Sample Calculations

Sample Calculations A-1

Physical Properties of the Air Stream

The viscosity of air-water vapor did not vary significantly from 48 per cent R.H. to 72 per cent R.H. The value of air-water vapor viscosity used in all calculations was 0.0440 pounds per foot per hour (6).

The density of air-water vapor did not vary significantly from 48 per cent R.H. to 72 per cent R.H. and barometric pressure from 728 to 740 millimeters of mercury. The air-water vapor density used in all calculations was 0.0707 pounds per cubic foot.

The average value of barometric pressure, 735 millimeters of mercury, was used in all calculations.

The diffusivity, D , was equal to 1.0 square feet per hour (4).

The Schmidt Number, $(\frac{\mu}{D\rho})$, was 0.636 in all calculations.

Sample Calculations A-2

Calculation of Experimental Liquid Film Thickness

Run No.	Flow Rate	Final Weight	Hold-up	Volume	Y
1	0.254 $\frac{\text{lbs.}}{\text{hr.}}$	1880 grams	229 grams	221 cm ³	0.073 cm
2	.151	1879	228.6	220.4	.073
3	.0754	1858.5	218.3	210.5	.071
4	.356	1926	252.2	243.7	.081
5	.192	1883	230.6	222.8	.074
6	.130	1876	227.1	219.4	.073
7	.537	1922	250.2	228.4	.076
8	.413	1918	248.1	226.4	.075
9	.167	1894	236	215.3	.071

Calculations and Constants:

$$\text{Area} = 3021 \text{ cm}^2$$

$$\text{Tare} = 1423 \text{ grams}$$

$$\text{Beam Factor} = 0.5013$$

$$\text{Hold-up} = (\text{Final Weight-Tare}) (\text{Beam Factor})$$

$$\text{Volume} = \frac{\text{Hold-up}}{\text{density}}$$

$$Y = \frac{\text{Volume}}{\text{Area}} = \text{Film Thickness}$$

To calculate the total thickness including cloth:

From Sample Calculations A-4 obtain the average cloth thickness and porosity, then;

(Average Cloth Thickness) (Area) (Porosity) = Volume available for liquid, and

(Volume) (Volume available for liquid) = excess volume, which is the liquid that flows on the outside of the cloth.

$\frac{(\text{excess volume})}{\text{area}} = \text{thickness of outside liquid film.}$

Total thickness = cloth thickness + outside liquid film.

Sample Calculations A-3

Theoretical Liquid Film Thickness on a Cloth Free Surface

Run No.	Feed Rate	$\Gamma(10^3)$	μ	ρ	$Y^3(10^6)$	$Y(10^2)$	Volume	Hold-up
1	0.254 $\frac{\text{lbs.}}{\text{hr.}}$.968	16	1.037	44.05	3.54	107cm ³	111gms.
2	.151	.576	16	"	26.20	2.97	89.8	93
3	.075	.286	16	"	13.02	2.35	71.1	74
4	.356	1.358	23	1.035	89.20	4.48	135.7	141
5	.192	.733	23	"	48.10	3.64	110.2	114
6	.130	.496	23	"	32.55	3.20	96.8	100
7	.537	2.048	7	1.096	36.45	3.32	100.4	110
8	.413	1.575	7	"	28.10	3.04	91.8	101
9	.167	.638	7	"	11.58	2.26	68.4	75

$$\Gamma = (\text{Feed Rate}) (3.82 \times 10^{-3})$$

$$Y = \left[\left(\frac{\Gamma \mu}{\rho} \right) 3.06 \times 10^{-3} \right]^{\frac{1}{3}}$$

$$\text{Tower Area} = 3021 \text{ cm}^3. \quad \text{Volume} = (Y) (\text{Tower Area}).$$

$$\text{Hold-up} = (V) (\rho).$$

Sample Calculations A-4

Thickness of the Cloth Covering

The thickness of the corduroy cloth covering was measured on a Frazier compressometer. The compressometer had a one inch diameter compression foot. The results of the thickness measurement at various pressures were as follows.

<u>Pressure</u>	<u>1st Run Thickness</u>	<u>2nd Run Thickness</u>	<u>Ave. Thickness</u>
0.10	0.0290 inches	0.0291 inches	0.0291 inches
.20	.0287	.0286	.0287
.35	.0284	.0285	.0285
.50	.0280	.0279	.0280
.75	.0275	.0274	.0275
1.00	.0273	.0273	.0273
1.50	.0265	.0265	.0265
2.00	.0259	.0260	.0260
2.50	.0255	.0254	.0255
3.00	.0245	.0247	.0246

A plot of the data is shown in Figure 1. The extrapolation to 0 pressure gave a thickness of .0295 inches.

The effect thickness was calculated from the measurement of r with a point micrometer.



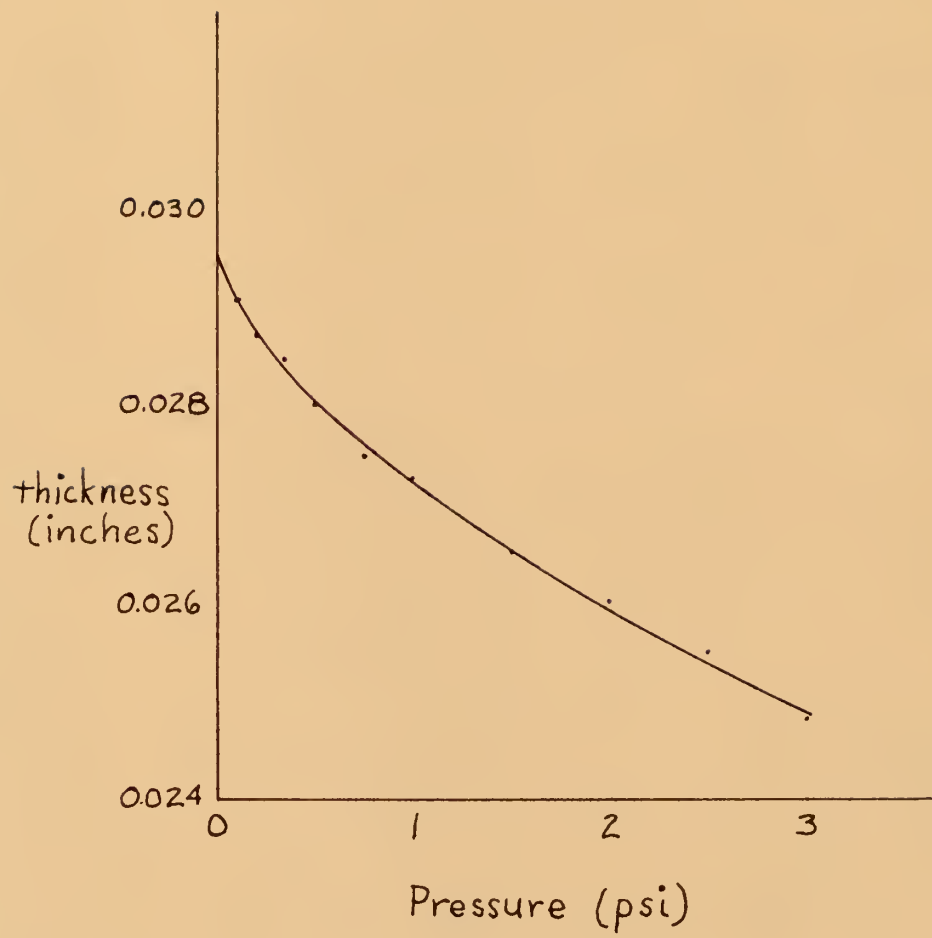
The number of ridges per inch and assuming the ridges were hemispheres gave an average thickness of 0.026 inches.

A section of corduroy cloth 87.25 cm long and 33.2 cm wide was weighed on a balance and found to weigh 59.210 grams.

The bulk density of the cloth was $0.309 \frac{\text{gm}}{\text{cm}^3}$.

The ratio was $.309 \text{ gm/cm}^3$ divided by 1.54 gm/cm^3 , the density of cotton, or 0.201.

The porosity was $(1-0.201) 100 = 77.9$ per cent.



Sample Calculations A-5

Determination of the best fit of the experimental data with the constants K_2 and K_3 .

$$\text{Let } \frac{K_2}{e^{K_3 P}} = X \quad ; \quad P = \frac{D_L \Theta}{Y^2}$$

Find the average value of P for each set of data.

Average P for ethylene glycol = 0.104

Average P for propylene glycol = 0.045

The constant, K_3 , was originally 5.121. A 50 per cent increase in K_3 gave K_3 equal to 7.65. A 30 per cent increase in $e^{K_3 P}$ for the ethylene glycol data resulted and a 12.5 per cent increase in $e^{K_3 P}$ for the propylene glycol data resulted.

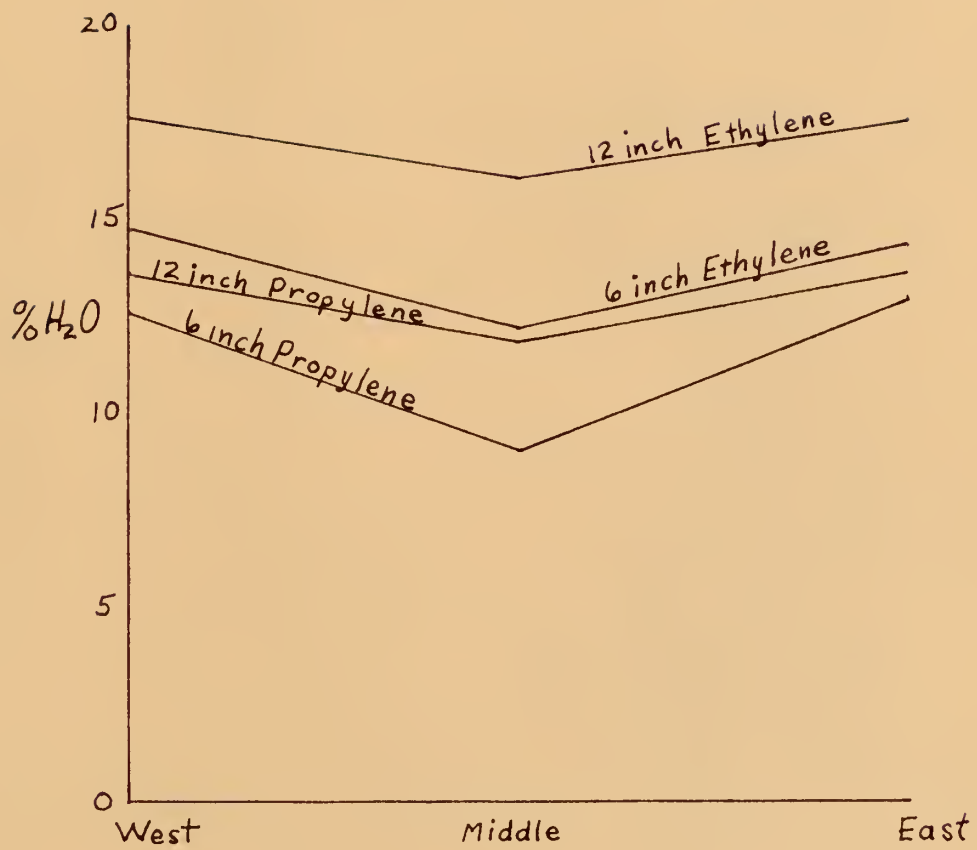
The value of K_2 was then changed to nullify the 12.5 per cent increase in the value of $e^{K_3 P}$ for the propylene glycol data. The net result of the manipulations was to decrease the value of $\frac{K_2}{e^{K_3 P}}$ by 12 per cent for the average of the ethylene glycol data while leaving the average of the propylene glycol data unchanged.

The above procedure was used at several different levels of increases in K_3 and K_2 . Samples of the experimental data were then run on the computer until the best fit was obtained.

EXPLANATION OF PLATE XXIV

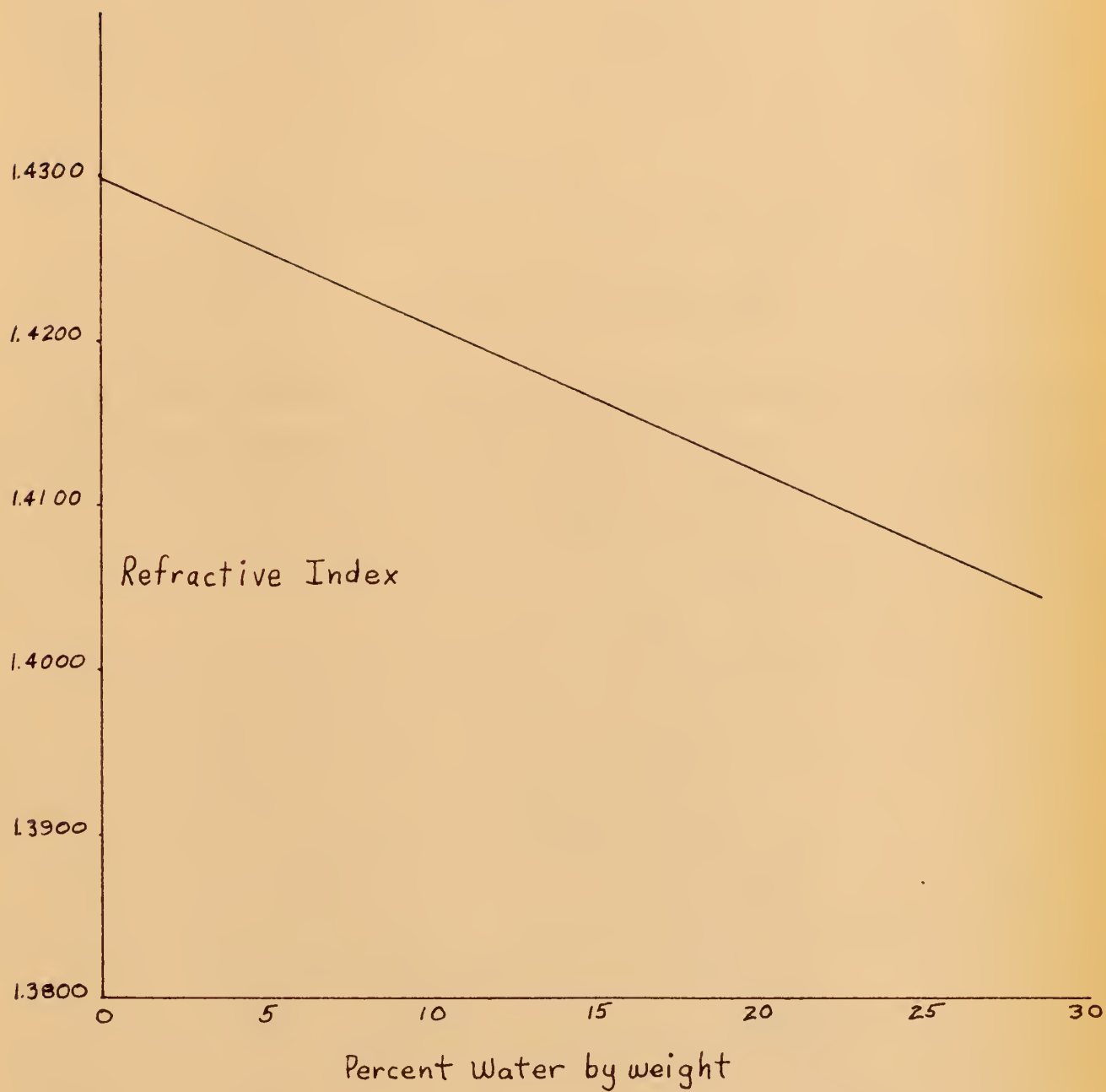
Plots of average concentration of traverse samples.

Data from Table A-3.



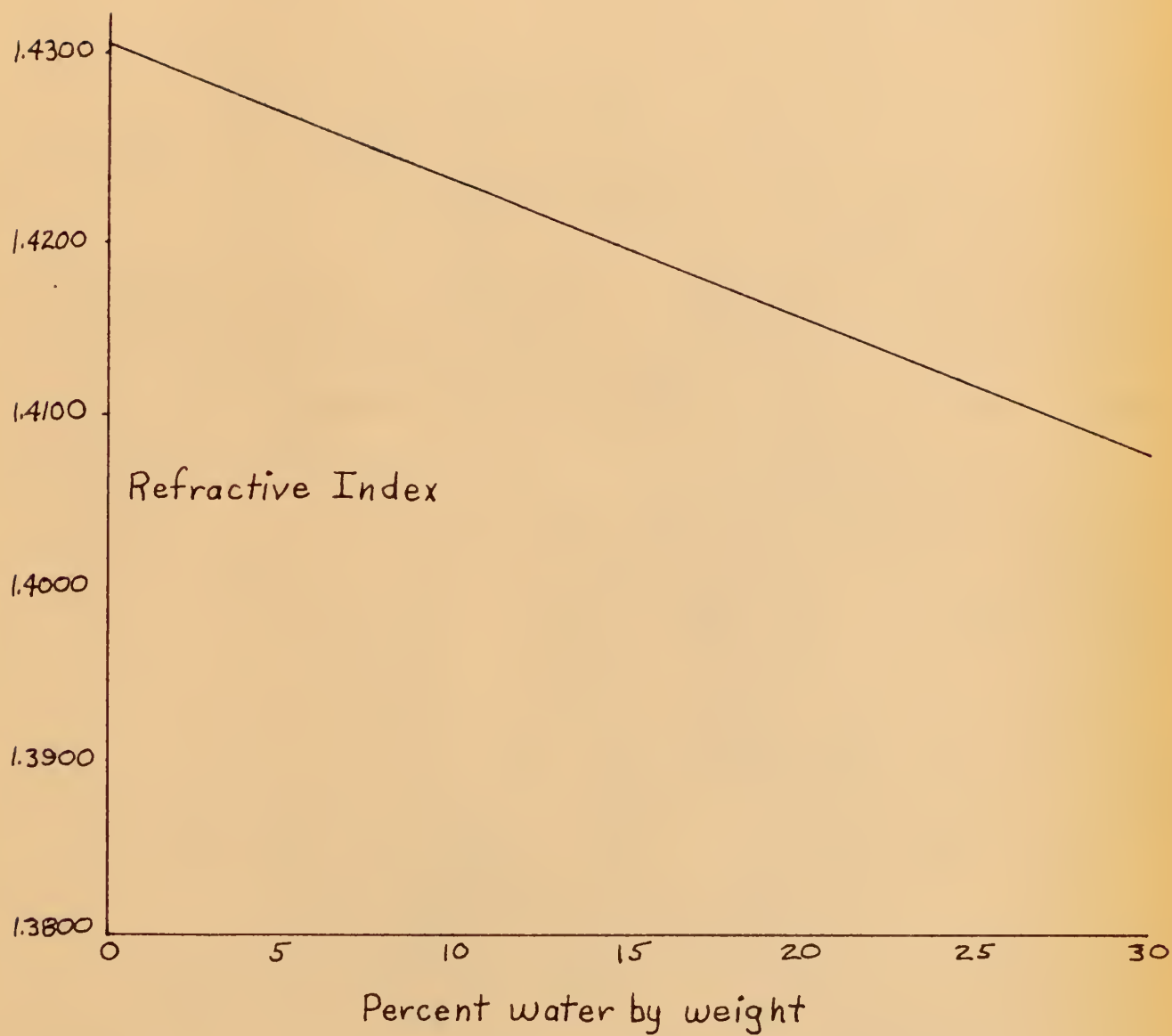
EXPLANATION OF PLATE XXV

Refractive index versus per cent of water by weight at 25° C.
Ethylene glycol solutions prepared by the Department of Chemistry, Kansas State University, Manhattan, Kansas.



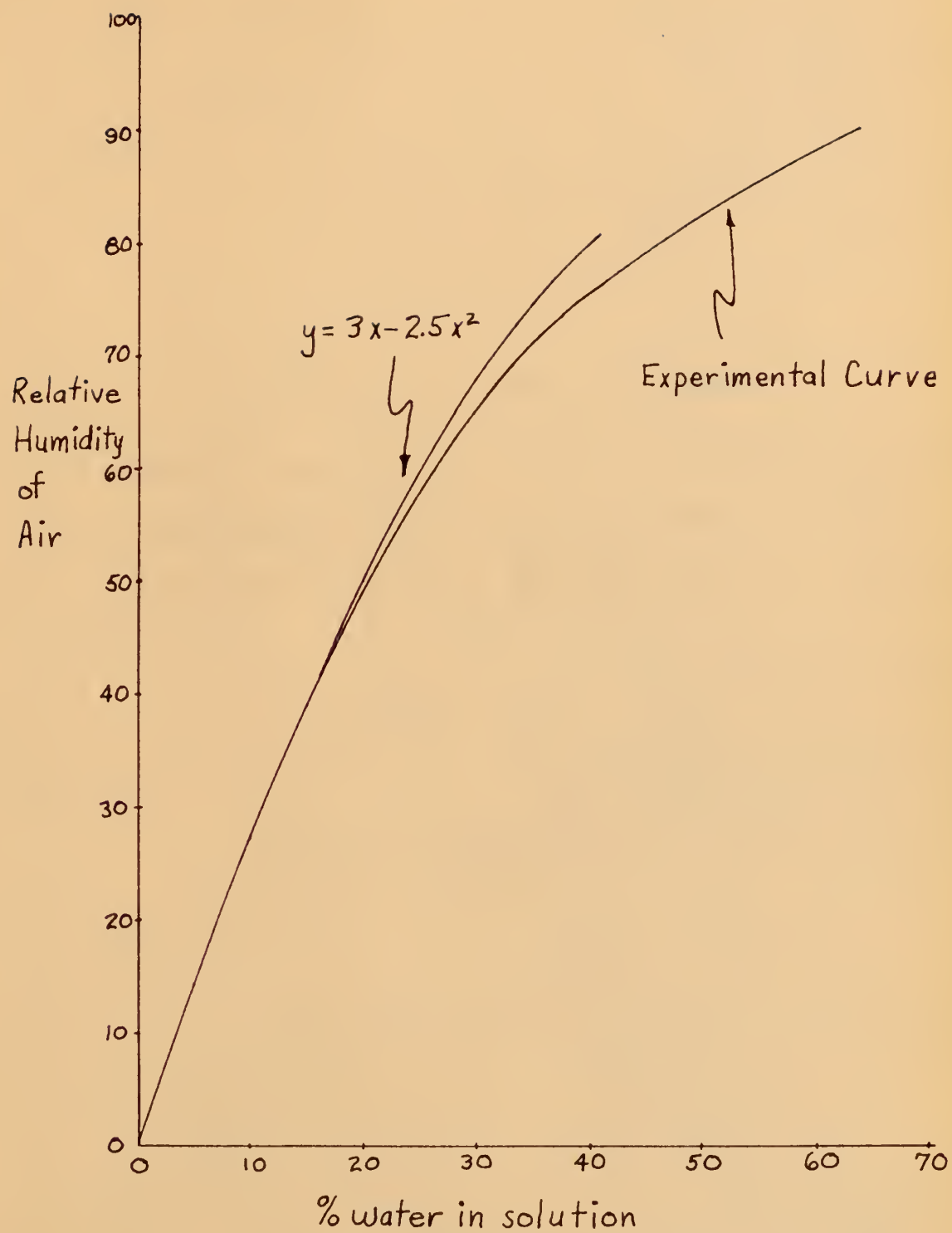
EXPLANATION OF PLATE XXVI

Refractive index versus per cent of water by weight at 25° C.
Propylene glycol solutions prepared by the Department of Chemistry, Kansas State University, Manhattan, Kansas.



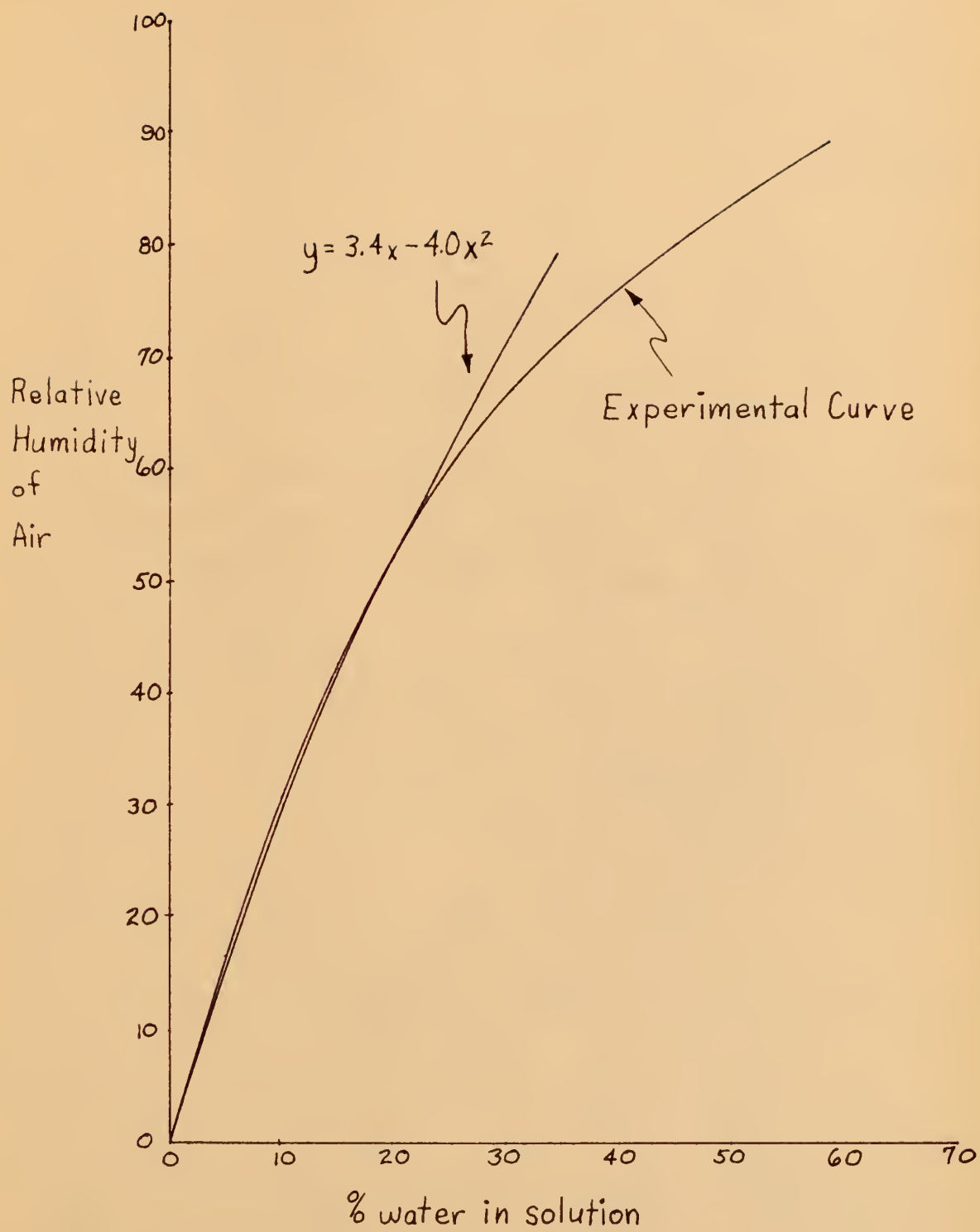
EXPLANATION OF PLATE XXVII

Polynomial approximation of water equilibrium between air and ethylene glycol solutions at 80° F. Experimental data from "Glycols", Dow Chemical Company, Midland, Michigan (7).



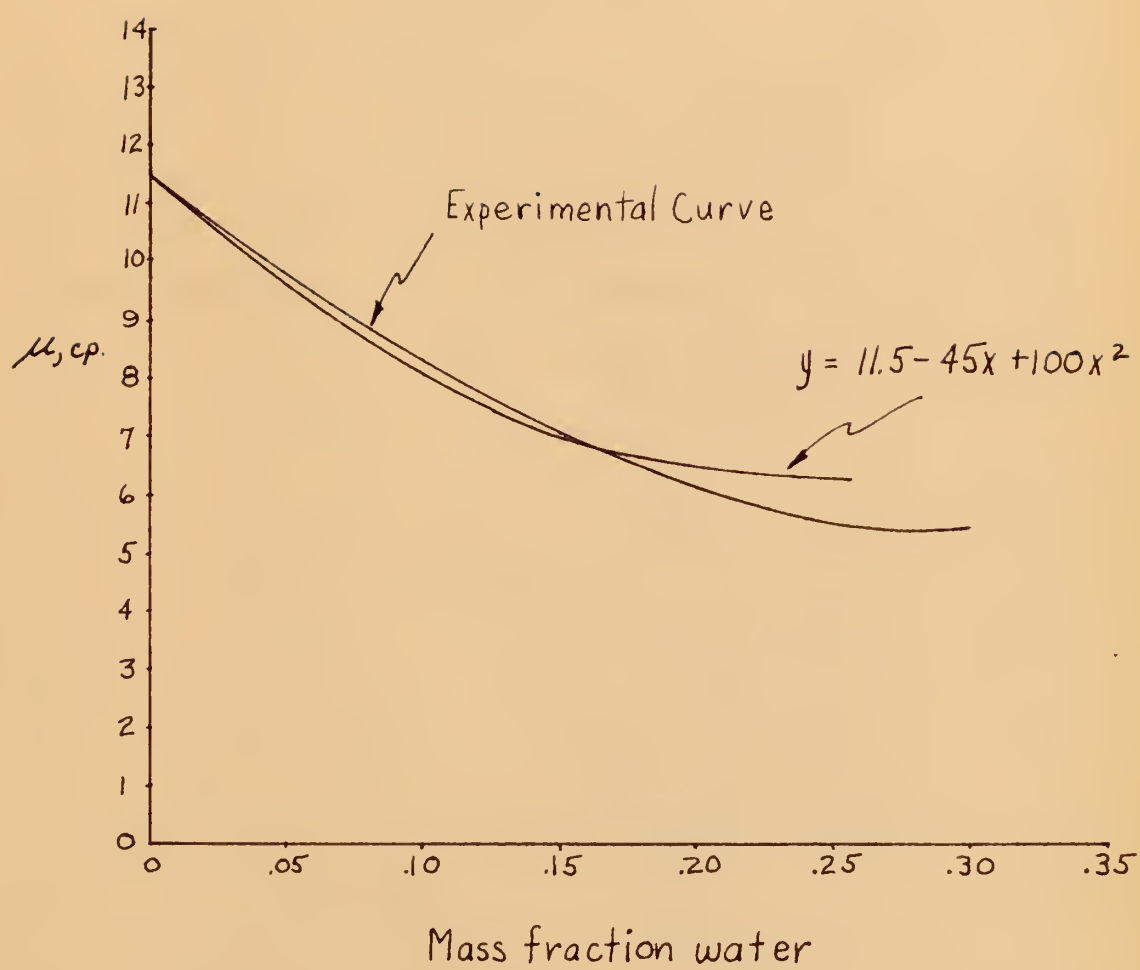
EXPLANATION OF PLATE XXVIII

Polynomial approximation of water equilibrium between air and propylene glycol solutions at 80° F. Experimental data from "Glycols", Dow Chemical Company, Midland, Michigan (7).



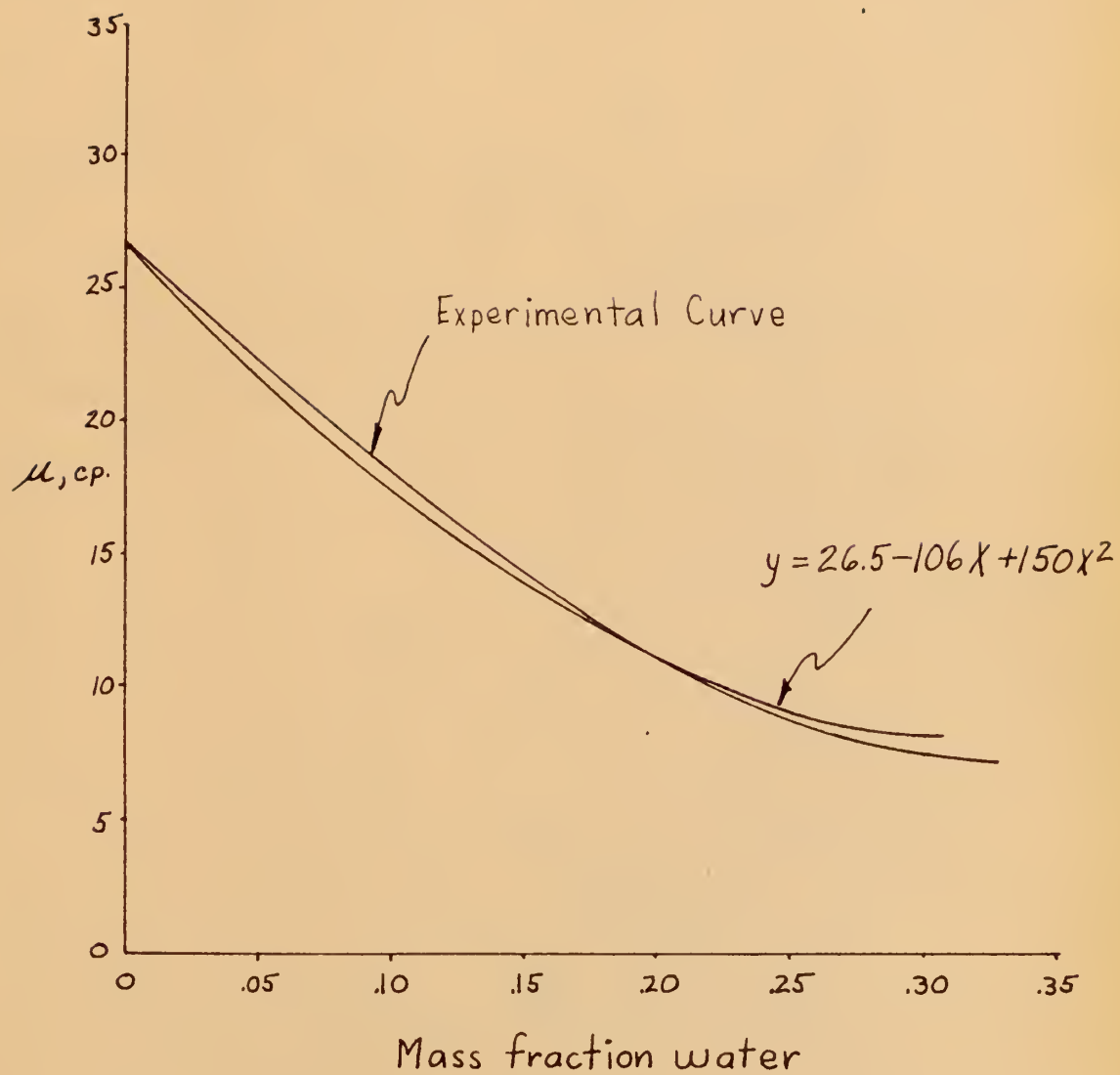
EXPLANATION OF PLATE XXIX

Polynomial approximation of ethylene glycol-water solution viscosity data at 80° F. Experimental data from "Glycols", Dow Chemical Company, Midland, Michigan (7).



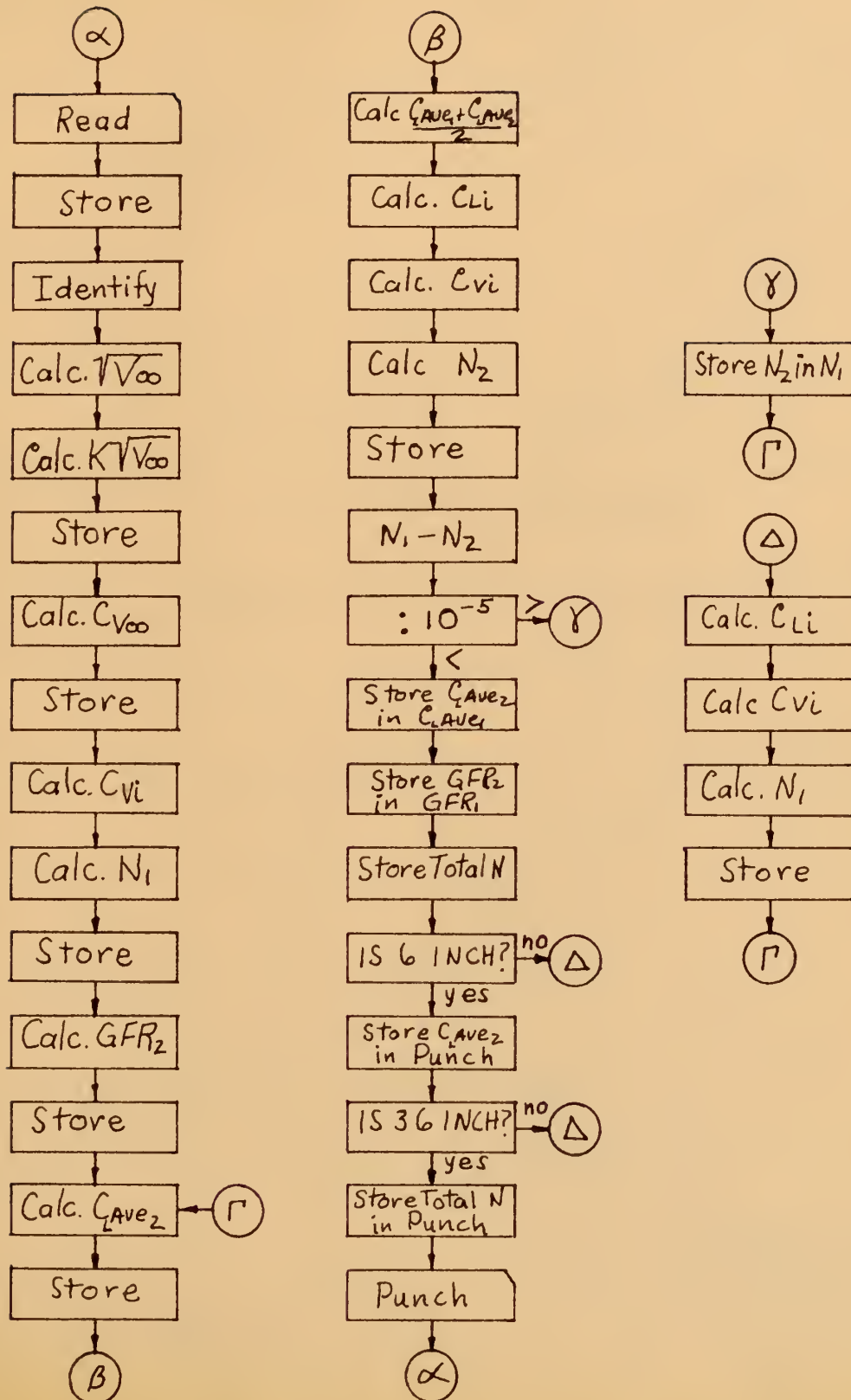
EXPLANATION OF PLATE XXX

Polynomial approximation of propylene glycol-water solution viscosity data at 80° F. Experimental data from "Glycols", Dow Chemical Company, Midland, Michigan (7).



EXPLANATION OF PLATE XXXI

Flow sheet for IBM 650 program.



EXPLANATION OF PLATE XXXII

The IBM 650 SOAP II Output Program

The main program has the constants for ethylene glycol. The eight cards listed at the end of the program are the propylene constants. To run the program with propylene data, place the propylene constants at the end of the program and proceed as usual. The program is in floating point arithmetic.

PLATE XXXII

1	MASS	TRANSFER	TO A	F	LAT	PLATE	1	0000	00	0000	0000		
1	TRANS	VERSE	CD	N	CENTR	A	TION	PRDF	2	0000	00	0000	0000
									3	0000	00	0000	0000
									4	0000	00	0000	0000
		BLR	1951	1960					5	0000	00	0000	0000
		REG	J1977	1986			PUNCH AREA		6	0000	00	0000	0000
1	READ								7	0000	70	1950	0050
		RCD	1950				DATA IN		8	0050	69	1951	0004
		LDD	1951				STORE AIR		9	0004	24	0007	0010
		STD	AFR				FLOW RATE		10	0010	69	1952	0005
		LDD	1952						11	0005	24	0008	0011
		STD	GFR				GLY F R		12	0011	69	1953	0006
		LDD	1953				STORES		13	0006	24	0009	0012
		STD	ICDNC				INITIAL CN		14	0012	24	0015	0018
		STD	TEST7						15	0018	69	1954	0057
		LDD	1954				STORES REL		16	0057	24	0060	0013
		STU	RELHU				HUM FRAC		17	0013	60	8002	0021
		RAU	8002				SETS LRS		18	0021	21	0026	0029
		STU	ABS08				ABSDRR O		19	0029	65	0007	0061
		RAL	AFR				WORD 1 PCH		20	0061	30	0002	0017
		SRT	0002						21	0017	35	0002	0023
		SLT	0002						22	0023	20	0027	0030
		STL	IDENT				XXXX000000		23	0030	65	0008	0063
		RAL	GFR						24	0063	30	0003	0071
		SRT	0003						25	0071	15	0027	0031
		ALO	IDENT				XXXXYY0000		26	0031	20	0027	0080
		STL	IDENT						27	0080	65	0009	0113
		RAL	ICDNC						28	0113	30	0006	0077
		SRT	0006						29	0077	15	0027	0081
		ALO	IDENT				XXXXYYZZ00		30	0081	20	0027	0130
		STL	IDENT						31	0130	65	0060	0065
		RAL	RELHU						32	0065	30	0008	0033
		SRT	0008						33	0033	15	0027	0131
		ALO	IDENT						34	0131	20	1977	0180
		STL	J0001						35	0180	60	0007	0111
		RAU	AFR						36	0111	39	0014	0064
		FMP	WINT						37	0064	21	0007	0110
		STU	AFR				START CALC		38	0110	60	0007	0161
		RAU	AFR						39	0161	69	0114	0067
HOWDY		LDD	HOWDY	EQQAX					40	0114	80	0000	0020
		RAA	0000						41	0020	82	0012	0076
		RAB	0012						42	0076	69	0079	0032
		LDD	COSTF						43	0032	24	0035	0038
BEGAN		STD	DEEDE	BEGAN					44	0038	39	0041	0091
		FMP	FRSTK						45	0091	21	0046	0049
		STU	MAINK				K X SQ RTV		46	0049	60	0002	0107
		RAU	MMHG						47	0107	39	0060	0160
		FMP	RELHU						48	0160	34	0163	0213
		FDV	TOTLP						49	0213	34	0016	0066
		FDV	VOLUM						50	0066	21	0070	0073
MARYA		STU	BULK	MARYA					51	0073	60	0009	0263
		RAU	ICDNC				EQUIL CALC		52	0263	39	0009	0059
		FMP	ICDNC						53	0059	39	0062	0112
		FMP	DNEFV						54	0112	21	0116	0019
		STU	KANDY						55	0019	60	0009	0313
		RAU	ICDNC						56	0313	39	0166	0216
		FMP	THREE						57	0216	33	0116	0043
		FSR	KANDY						58	0043	21	0116	0069
NEWLP		STU	KANDY	PAN					59	0100	60	0009	0363
		RAU	ICDNC						60	0363	39	0009	0109
		FMP	ICDNC						61	0109	21	0164	0117
		STU	DONT1						62	0117	60	0120	0025
		RAU	COST1						63	0025	39	0164	0214
		FMP	DONT1						64	0214	21	0164	0167
		STU	DONT1						65	0167	60	0009	0413
		RAU	ICDNC						66	0413	39	0266	0316
		FMP	COST2						67	0316	21	0170	0123
		STU	DONT2						68	0123	60	0126	0181
		RAU	COST3						69	0181	33	0170	0047
		ESB	DONT2						70	0047	32	0164	0141
		FAO	DONT1						71	0141	21	0096	0099
		STU	FINAL						72	0099	60	0052	0157
		RAU	COST5						73	0157	34	0096	0146
		FDV	FINAD						74	0146	21	0150	0003
		STU	FINAD						75	0003	60	0056	0211
		RAU	ELNAE						76	0211	39	0264	0314
		FMP	COST8						77	0314	34	0008	0058
		FDV	GFR						78	0058	39	0150	0200
		FMP	FINAD						79	0200	34	0056	0106
		FDV	FINAE						80	0106	34	0056	0156
		FDV	FINAE						81	0156	39	0159	0209
		FMP	COSTD						82	0209	21	0364	0217
		STU	FINAH						83	0217	60	0364	0119
MARYE		RAU	FINAH						84	0119	69	0022	0075
		LDD	MARYE	EOOLR					85	0022	21	0176	0129
		STU	FINAJ						86	0129	60	0082	0037
		RAU	COSTB						87	0037	34	0176	0226
		FDV	FINAJ						88	0226	21	0230	0083
		STU	FINAK						89	0083	60	0036	0191
		RAU	COSTC						90	0191	33	0230	0207
		FSR	FINAK						91	0207	21	0162	0115
		STU	FINAR						92	0115	60	0015	0169
		RAU	TEST7						93	0169	39	0230	0280
		FMP	FINAK						94	0280	21	0034	0087
		STU	TEST8						95	0087	60	0009	0463
		RAU	ICDNC						96	0463	33	0034	0261
		FSR	TEST8						97	0261	34	0162	0212
		FDV	FINAR						98	0212	21	0366	0219
		STU	FINAM						99	0219	39	0366	0416
		FMP	FINAM						100	0416	39	0062	0262
		FMP	DNEFV						101	0262	21	0116	0269
		STU	KANDY						102	0269	60	0366	0121
		RAU	FINAM						103	0121	39	0166	0466
		FMP	THREE						104	0466	33	0116	0093
		FSR	KANDY						105	0093	21	0116	0069
PAN		STU	KANDY	PAN					106	0069	60	0002	0257
		RAU	MMHG						107	0257	39	0116	0516
		FMP	KANDY						108	0516	34	0163	0513
		FDV	TOTLP						109	0513	34	0016	0566
		FDV	VOLUM						110	0566	21	0220	0173
		STU	INTRC				IFCE AIR C		111	0173	60	0070	0125
		RAU	BULK						112	0125	33	0220	0097
		FSR	INTRC						113	0097	39	0046	0196
		FMP	MAINK						114	0196	39	0149	0199
		FMP	FEETO						115	0199	39	0102	0152
		FMP	MMH20				LRS H20 IN						

PLATE XXXII (cont.)

MARYB	STU	T8ALE	MARYB	116	0152	21	0206	0259
	RAU	GFR		117	0259	60	0008	0563
	FAD	T8ALE		118	0563	32	0206	0133
	STU	GFR2		119	0133	21	0088	0241
	RAU	GFR		120	0241	60	0008	0613
	FMP	ICONC		121	0613	39	0009	0309
	FAD	T8ALE		122	0309	32	0206	0183
	FOV	GFR2	PCTH20AT 2	123	0183	34	0088	0138
	STU	SCONC		124	0138	21	0042	0045
	FAO	ICONC		125	0045	32	0009	0085
	FDV	TWOD0	AVE CONC 2	126	0085	34	0188	0238
	STU	ITER1	EQUIL CALC	127	0238	21	0092	0095
	FMP	ITER1		128	0095	39	0092	0142
	STU	ODNT1		129	0142	21	0164	0267
	RAU	COST1		130	0267	60	0120	0175
	FMP	ODNT1		131	0175	39	0164	0414
	STU	ODNT1		132	0414	21	0164	0317
	RAU	ITER1		133	0317	60	0092	0147
	FMP	COST2		134	0147	39	0266	0616
	STU	ODNT2		135	0616	21	0170	0223
	RAU	COST3		136	0223	60	0126	0231
	FSR	ODNT2		137	0231	33	0170	0197
	FAO	ODNT1		138	0197	32	0164	0291
	STU	FINAL		139	0291	21	0096	0249
	RAU	COST5		140	0249	60	0052	0307
	FDV	FINAL		141	0307	34	0096	0245
	STU	FINAD		142	0245	21	0150	0053
	RAU	FINAE		143	0053	60	0056	0311
	FMP	COST8		144	0311	39	0264	0464
	FOV	GFR2		145	0464	34	0088	0288
	FMP	FINAD		146	0288	39	0150	0250
	FDV	FINAE		147	0250	34	0056	0256
	FOV	FINAE		148	0256	34	0056	0306
	FMP	COSTD		149	0306	39	0159	0359
	STU	FINAH		150	0359	21	0364	0367
	RAU	FINAH		151	0367	60	0364	0319
	LDO	MARYJ	EOOLR	152	0319	69	0072	0075
MARYJ	STU	FINAJ		153	0072	21	0176	0172
	RAU	COST8		154	0179	60	0082	0137
	FOV	FINAJ		155	0137	34	0176	0276
	STU	FINAK		156	0276	21	0230	0233
	RAU	COSTC		157	0233	60	0036	0341
	FSR	FINAK		158	0341	33	0230	0357
	STU	FINAR		159	0357	21	0162	0165
	RAU	TEST7		160	0165	60	0015	0369
	FMP	FINAK		161	0369	39	0230	0330
	STU	TEST8		162	0330	21	0034	0187
	RAU	ITER1		163	0187	60	0092	0247
	FSR	TEST8		164	0247	33	0034	0361
	FDV	FINAR		165	0361	34	0162	0312
FAN	STU	ITER1	FAN	166	0312	21	0092	0145
	FMP	ITER1		167	0145	39	0092	0192
	FMP	ONEFV		168	0192	39	0062	0362
	STU	KENOY		169	0362	21	0666	0419
	RAU	ITER1		170	0419	60	0092	0297
	FMP	THREE		171	0297	39	0166	0716
	FSR	KENDY		172	0716	33	0666	0143
	STU	KENY		173	0143	21	0666	0469
	FMP	MHHG		174	0469	39	0002	0202
	FOV	TOTLP		175	0202	34	0165	0263
	FDV	VOLUM		176	0263	34	0016	0666
	STU	INTRO		177	0666	21	0270	0273
	RAU	BULKK		178	0273	60	0070	0225
	FSR	INTRO		179	0225	33	0270	0347
	FMP	MAINK		180	0347	39	0046	0296
	FMP	FEETQ		181	0296	39	0149	0299
	FMP	MWH20	LRSH20GAIN	182	0299	39	0102	0252
	STU	BTALE		183	0252	21	0356	0409
	RAU	T8ALE		184	0409	60	0206	0411
	FSR	BTALE		185	0411	33	0356	0283
	STU	GLASS	OIFF 1 2	186	0283	21	0338	0391
	RAU	STNDO		187	0391	60	0044	0349
	FSM	GLASS	STANDARD	188	0349	38	0338	0215
	BMI	HIKKI	COMPARISON	189	0215	46	0068	0519
HIKKI	LDO	BTALE		190	0068	69	0356	0459
HAKKY	STU	T8ALE	MARYB	191	0459	24	0206	0259
	LDO	SCONC	CONT ITER	192	0519	69	0042	0195
	STU	ICONC		193	0195	24	0009	0412
	LDO	GFR2		194	0412	69	0088	0441
	STU	GFR		195	0441	24	0008	0281
	RAU	ABSOR		196	0441	60	0026	0281
	FAO	T8ALE		197	0281	32	0206	0333
	STU	ABSOR		198	0333	21	0026	0229
	SX8	0001		199	0229	53	0001	0135
	NZ8	NEWLP	STRES IS 6 INCH	200	0135	42	0100	0039
SIRES	AXA	0001		201	0039	50	0001	0245
	LDO	SCONC		202	0245	69	0042	0295
	STU	JOOO1	A	203	0295	24	3977	0380
	RAU	DEEDE		204	0380	60	0035	0089
	SUP	COSTG		205	0089	11	0242	0397
	STU	DEEDE		206	0397	21	0035	0388
	NZU	MARYC	POUND	207	0388	44	0491	0292
MARYC	RAB	0012	NEWLP	208	0491	82	0012	0100
POUND	AXA	0001		209	0292	50	0001	0048
	LDO	ABSOR		210	0048	69	0026	0279
	STU	JOOO1	A	211	0279	24	3977	0430
	PCH	1977	REAO	212	0430	71	1977	0000
FOOAX	STU	SORT1	END	213	0067	24	0320	0323
	NZE	0001		214	0323	45	0326	0320
	BMI	SORT2	SORT1	215	0326	46	0329	0480
	STU	SORT3		216	0480	21	0084	0237
	STU	SORT4	SORT5	217	0237	24	0040	0193
SORT5	FDV	SORT4		218	0193	34	0040	0090
	FAD	SORT4		219	0090	32	0040	0417
	FOV	FPTWO		220	0417	34	0370	0420
	STU	SORT6		221	0420	21	0024	0127
	FSR	SORT4		222	0127	33	0040	0467
	FOV	SORT4		223	0467	34	0040	0140
	RAM	8003		224	0140	67	8003	0447
	RAU	8002		225	0447	60	8002	0055
	FSR	SIZE8		226	0055	33	0108	0185
	BMI	SORT7		227	0185	46	0438	0139
	LDO	SORT6		228	0139	69	0024	0177
	STU	SORT4		229	0177	69	0044	0243
	RAU	SORT3	SORT5	230	0243	60	0084	0193
SORT7	RAU	SORT6	SORT1	231	0438	60	0024	0320

PLATE XXXII (cont.)

SQRT2	HLT	HH88	HH88	020	232	0329	01	8888	8888
FPTW0	20	0000	0051	021	233	0370	20	0000	0051
SIZE8	10	0000	0043	022	234	0108	10	0000	0043
FEETQ	45	2000	0049		235	0149	45	2000	0049
MINTE	60	0000	0052		236	0014	60	0000	0052
STND0	10	0000	0046		237	0044	10	0000	0046
ONFFV	25	0000	0051		238	0062	25	0000	0051
THREE	30	0000	0051		239	0166	30	0000	0051
TW000	20	0000	0051		240	0188	20	0000	0051
MWH20	18	0000	0052		241	0102	18	0000	0052
FRSTK	31	2000	0050		242	0041	31	2000	0050
VOLUME	40	7000	0053		243	0016	40	7000	0053
TOTLP	73	5000	0053		244	0163	73	5000	0053
MMHG	26	2000	0052		245	0002	26	2000	0052
COST1	10	0000	0053		246	0120	10	0000	0053
COST2	45	0000	0052		247	0266	45	0000	0052
COST3	11	5000	0052		248	0126	11	5000	0052
COST5	37	9000	0046		249	0052	37	9000	0046
COST7	11	0000	0051		250	0300	11	0000	0051
COST8	36	4000	0053		251	0264	36	4000	0053
COSTA	88	2000	0050		253	0082	88	2000	0050
COSTC	10	0000	0051		254	0036	10	0000	0051
COSTD	76	5000	0051		255	0159	76	5000	0051
CASIF	00	0000	0006		256	0079	00	0000	0006
COSTG	00	0000	0001		257	0242	00	0000	0001
FINAE	89	0000	0049		258	0056	89	0000	0049
FOOLR	STU	EXP02		001	259	0075	24	0028	0331
	STU	EXP03		002	260	0331	21	0086	0189
	LOO	8007		003	261	0189	69	8007	0345
	STO	EXP04		004	262	0345	24	0098	0001
	RAC	0000		005	263	0001	88	0000	0407
	RAU	EXP03		006	264	0407	60	0086	0541
	RMI	EXP05	EXP06	007	265	0541	46	0094	0395
EXP06	FSR	LNTEN		008	266	0395	33	0148	0275
	RMI	EXP07		009	267	0275	46	0078	0379
	AXC	0001	EXP06	010	268	0379	58	0001	0395
EXP07	FAO	LNTEN	EXP08	011	269	0078	32	0148	0325
EXP05	SXC	0001		012	270	0094	59	0001	0400
	FAO	LNTEN		013	271	0400	32	0148	0375
	RMI	EXP05	EXP08	014	272	0375	46	0094	0325
	STU	EXP03		015	273	0325	21	0086	0239
EXP08	STU	EXP09		016	274	0239	21	0144	0497
	RAL	EXP04		017	275	0497	65	0098	0103
	LOO	8007		018	276	0103	69	8007	0509
	STU	EXP04		019	277	0509	24	0098	0051
	RAC	8002		020	278	0051	88	8002	0559
	LDO	FPONE		021	279	0559	69	0462	0265
	STO	EXP10		022	280	0265	24	0118	0171
EXP12	STO	EXP11	EXP12	023	281	0171	24	0074	0227
	RAU	EXP10		024	282	0227	60	0118	0373
	FAO	EXP09		025	283	0373	32	0144	0221
	STU	EXP10		026	284	0221	21	0118	0271
	RAU	EXP11		027	285	0271	60	0074	0429
	FAO	FPONE		028	286	0429	32	0462	0289
	STU	EXP11		029	287	0289	21	0074	0277
	RAU	EXP09		030	288	0277	60	0144	0399
	FMP	EXP03		031	289	0399	39	0086	0136
	FOV	EXP11		032	290	0136	34	0074	0124
	STU	EXP09		033	291	0124	21	0144	0547
	FOV	EXP10		034	292	0547	34	0118	0168
	FSR	SIZE8		035	293	0168	33	0108	0235
	RMI		EXP12	036	294	0235	46	0488	0227
	RAU	EXP10		037	295	0488	60	0118	0423
	AUP	EXP04	EXP02	038	296	0423	10	0098	0028
FPONE	10	0000	0051	039	297	0462	10	0000	0051
SIZE8	10	0000	0043	040	298	0108	10	0000	0043
LNTEN	23	0258	5151	041	299	0148	23	0258	5151

PROPYLENE CONSTANTS

6119541953	2400628000	4000000051
6119541953	2401668000	3400000051
6119541953	2401208000	1500000053
6119541953	2402668000	1060000053
6119541953	2401268000	2650000052
6119541953	2400528000	4190000046
6119541953	2403008000	1035000051
6119541953	2402648000	3430000053

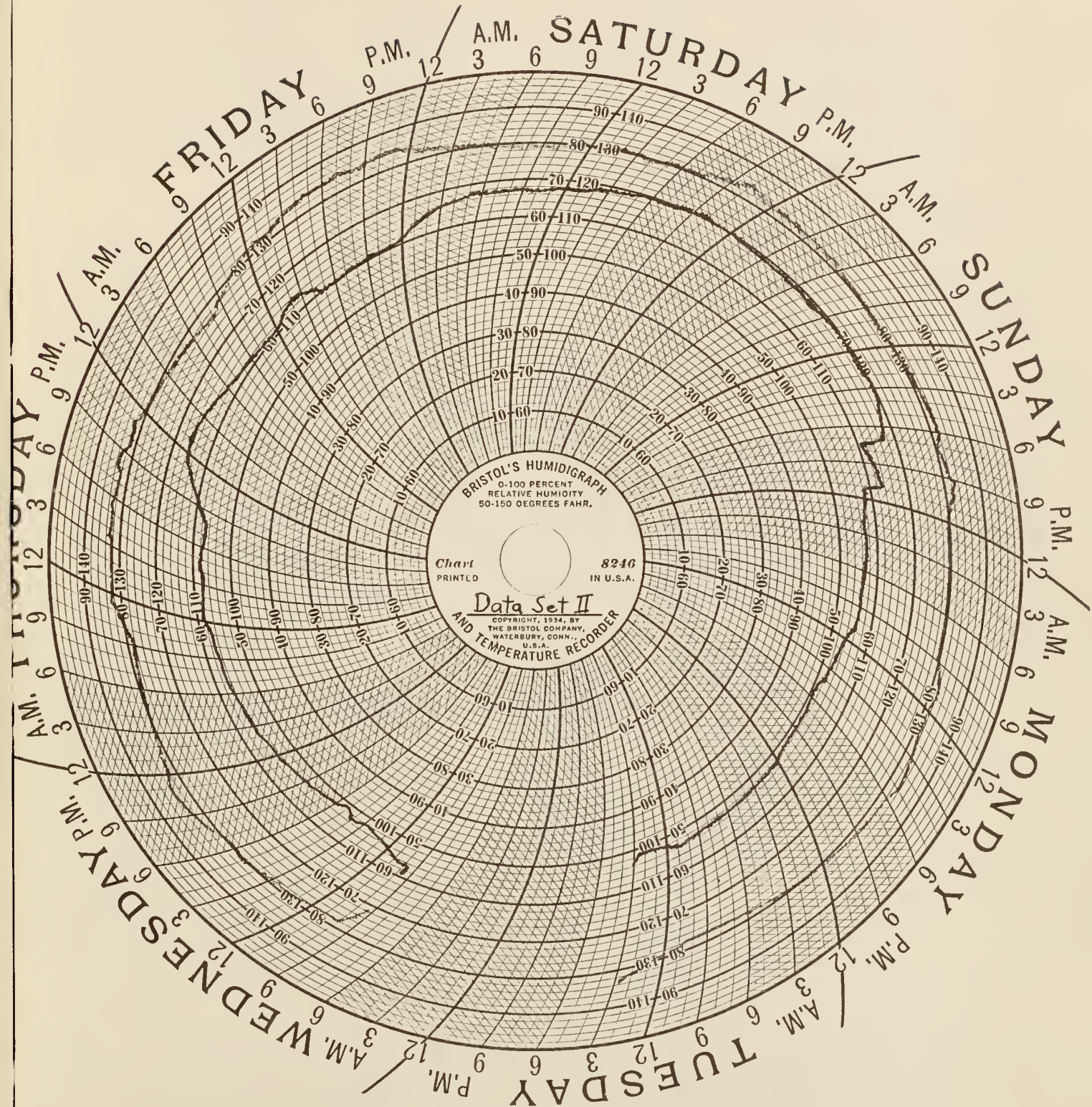
EXPLANATION OF PLATE XXXIII

Bristol recorder chart

Upper line-temperature

Lower line-relative humidity

PLATE XXXIII



MASS TRANSFER TO A FALLING LIQUID ON A FLAT PLATE
WITH TRANSVERSE CONCENTRATION GRADIENTS AND
WITH CONSTANT HOLD-UP AND VARIABLE LIQUID FEED

by

JACKIE JOE LONSINGER

B. S., Kansas State University, 1960

AN ABSTRACT OF A MASTER'S THESIS

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requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1962

Two phase mass transfer was studied in which water was absorbed from air with ethylene and propylene glycol.

The mass transfer system was designed such that the liquid flowed in a thin film on a vertical tower (flat plate) and the air moved past the tower in a horizontal direction; the liquid-vapor interface was parallel to the direction of air flow. The surface of the tower was provided with a hold-up media such that the quantity of liquid on the tower was essentially constant throughout the liquid flow rates studied.

The system was three dimensional in that the water concentration in the liquid phase was a function of y and z position while the water concentration in the vapor phase was a function of the y and x position. A mass transfer model was developed that employed, with empirical modification, (1) known relationships between rates of transfer and concentrations in the gas phase, (2) known relationships between rates of transfer and concentrations in the liquid phase, and (3) matched the liquid phase relationships and the gas phase relationships by an iterative procedure on a digital computer.

The experimental data showed that the absorption rate increased with increasing glycol solution flow rate and with increasing relative humidity, but showed no trend with increasing air flow rate.

The calculated liquid concentration profiles in the z direction compared favorably with the experimental concentration profiles.

The model as developed may be employed to predict concentration profiles in the z direction, and subsequently quantities of material transferred, for systems of comparable geometry and operating conditions.